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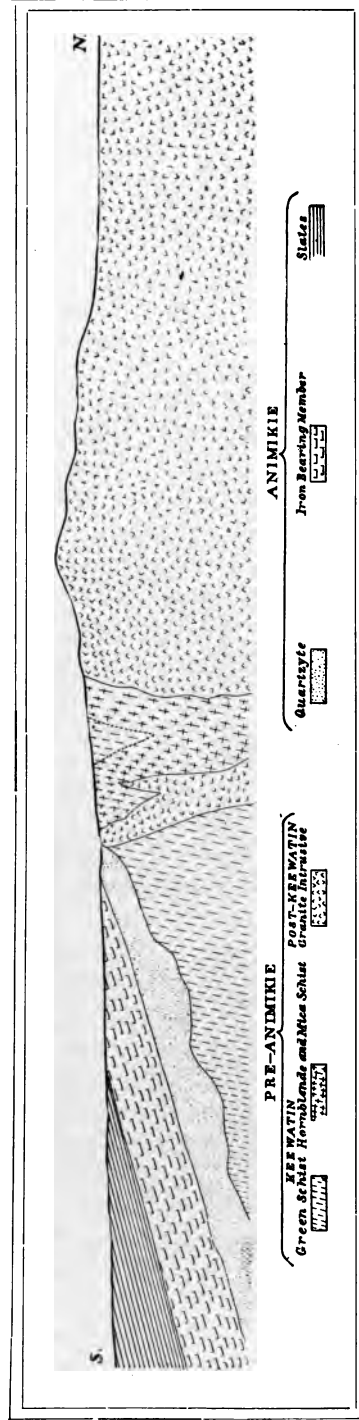


FIG 1.—SECTION ACROSS THE MESABI RANGE.

DRAWN NORTH AND SOUTH THROUGH THE CENTRAL PARTS OF TOWNSHIPS 58-18 AND 59-18, THUS PASSING THROUGH THE TOWN OF MOUNTAIN IRON.

Horizontal Scale $\frac{1}{4}$ mile=1 inch. Vertical Scale three or four times exaggerated.

This section shows the typical stratigraphy of the Western Mesabi range.

Minnesota Geological Survey

GEOLOGICAL AND NATURAL HISTORY SURVEY OF MINNESOTA
N. H. WINCHELL, STATE GEOLOGIST.

BULLETIN NO. X.

THE IRON-BEARING ROCKS

1894

OF THE

MESABI RANGE

IN MINNESOTA.

BY J. EDWARD SPURR.

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PREFACE.

In this bulletin the writer has endeavored to add to the knowledge of one of the most perplexing and fascinating fields in American geology. At the same time, some apology must be offered for the incompleteness of the work. Both time and opportunity have been too scanty for a thorough study and analysis of all of the problems which have presented themselves. New modifications of old principles, and new principles, will be found to have been active in other areas, apart from that especially studied; and, not improbably, in this area itself. Economic geology in these departments is as yet rudimentary; but it is hoped that the main points here presented will prove sound, and can safely be made the basis for more advanced work.

In the preparation of this subject, aid of the greatest value has been rendered by many friends in Massachusetts and Minnesota. The writer is especially grateful to Mr. H. V. Winchell of Minneapolis, to Professor J. E. Wolff and Dr. R. T. Jackson of Harvard University, and to Professor N. H. Winchell and Dr. U. S. Grant of the Minnesota survey.

J. E. SPURR.

Minneapolis, April 30, 1894.

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CHAPTER I.

GENERAL STRUCTURE OF THE MESABI RANGE IN THE IRON-BEARING REGION.

THE KEEWATIN SERIES.

The lowest rocks of the iron-producing region are in part certain greenish schists which are profoundly metamorphosed. For this reason it is difficult to decide in any given case what was the original nature of the rock, for most of the original mineral characters have disappeared. It seems clear, however, that some of them are derived from clastic rocks—slates, quartzites, graywackes, etc., while others have an igneous origin. All of these rocks have been changed and brought to resemble one another in some degree by dynamic forces, which have induced re-crystallization and the development of certain minerals common to all. One of the most marked effects of these disturbances is a regional cleavage, which is nearly uniform,—in trend, about N. 70° E., in hade approaching the vertical. (See Fig. 1.)

These Keewatin schists are exposed upon the south slope of the Giant's range of hills, or that region which goes under the name of the Mesabi Iron range, to a limited extent only. In general terms, they form a narrow strip, somewhat less than a mile in width, running in a north of east direction from the middle of the extreme southern part of T. 59-18 to the Embarras lakes and eastward. They there seem to disappear, but reappear again in the same position further east. West of range 18 they are found only in isolated patches, along the line which is given by the continuation of the principal strip. There is an exceptional occurrence in T. 58-17, where a tongue of the Keewatin* schists runs southwest across the town, quite to its

*The terms Keewatin and Anmikkie are used by the Minnesota survey to designate formations which correspond in general to the Huronian of the United States survey,—the Keewatin being in the Lower, the Anmikkie constituting the Upper Huronian.

southern border, and just enters the northern limit of T. 57-17.

The most common phase of these schists upon the Mesabi range, is that which goes by the common name of "green schist." This has a fine texture and is chiefly distinguished by the development of sericite and kindred minerals along the cleavage surfaces, and hence generally throughout the rock. Along the northern edge of the Keewatin area, these schists come in contact with granite, and here, in many cases, there has been a more complete crystallization, resulting in the formation of limited areas of hornblende and mica schists, sometimes coarsely crystalline. On the extreme southern limit, on the other hand, there is less change, as in the southern part of the area which runs across T. 58-17. Here, in many cases, the schists resemble closely little-altered sedimentary rocks.

GRANITE.

Next in order of age is the granite, of which the highest part of the Giant's range consists. South of this ridge of hills it is not found to any extent, but it runs north, making for some distance the northern slope of the divide. In shape, the granite area is long and narrow, constituting a belt which traverses nearly the whole Mesabi region in Minnesota. The width of this strip averages perhaps nearly ten miles, and the direction is about N. 70° E., or about the same as the trend of the schistosity in the Keewatin rocks. The relation of the granite to the schists is plainly intrusive. It cuts the schists at the contact, and sends small stringers into them; near the edge of the granite area there are imbedded numerous fragments of the schists, more or less profoundly metamorphosed and re-crystallized, according to the size of the fragment, and the distance from the contact; and along the contact, and especially where some slight irregularity in the course of the granite runs, so as to partly surround a fragment of the Keewatin, portions of the main body of the schist have been metamorphosed, as before stated, into more perfectly crystalline hornblende and mica schists. The same proofs of the intrusive nature of the granite have been found, and stated by Dr. U. S. Grant, for the region further east.* So it is quite proper to speak of the Giant's range granite as a dike, which

*Twentieth Ann. Rep., Geol. and Nat. Hist. Survey of Minnesota, "Field Observations on Certain Granite Areas," pp. 35-95. Twenty-first Ann. Rep. pp. 36-37

came up nearly vertically into the Keewatin rocks. The age of this dike is not closely fixed, except that it is, of course, younger than the Keewatin period, and far older than the lowest rocks of the overlying Animikie strata. In the tongue of Keewatin rocks which runs down into township 58-17, there are found two lenticular masses of the granite, surrounded by the schists. Of these the smallest is farthest from the main body of granite, being situated in sections 20 and 21, T. 58-17. It has a length of about three-quarters of a mile, and a width of a few hundred yards. The larger one has a length of nearly three miles, and a width at the middle of about three-quarters of a mile. It crosses the range line between T. 58-17 and T. 58-16, in the northern part of the townships. The longer axes of these two masses are in a common direction, and correspond with the general trend of the main body. They are undoubtedly the surface exposures of apophyses from the main dike.

Petrographically, the granite of the Giant's range is a hornblende granite, which in various parts of the field is modified by the varying increase or diminution of any of the constituents. Besides the variations of mineral composition, there are also great differences of texture, due in the main to the relative proximity of the Keewatin rocks. Near this contact the granite becomes fine-grained and gneissic; but it grows coarser as the distance increases, and becomes often coarsely porphyritic. The granite of the apophyses is of the same mineral composition as the rest, and in its finer texture corresponds exactly to the common fine-grained phase found at the contact of the main dike with the schists.

THE ANIMIKIE SERIES.

Unconformably upon the folded and schistose rocks of the Keewatin and the granite lies the Animikie series. The comparison of these two formations shows the immense time-break which this unconformity represents. None of the forces which have changed the Keewatin have operated upon the Animikie series, for here there is neither any marked folding nor schistose structure, nor any other evidence of great disturbance. The Keewatin rocks were altered to their present condition quite completely before the lowest of the Animikie strata were laid down. Thus, between the deposition of the rocks of these two formations, there intervened vast periods of disturbance,

producing intricate and complex folds, the intrusion of the granite, and the development of the regional schistosity. But since the beginning of the Animikie period, this region has been left comparatively undisturbed by dynamic forces.

The main part of the Animikie series in Minnesota, and all that part which includes the known iron-bearing region, lies to the south of the granite of the Giant's range, and constitutes, for the most distance, the immediate southern slope of the divide. It thus forms a belt which extends from the Mississippi river to the extreme northeastern part of Minnesota, at Pigeon point, and into Canada, to Thunder bay. In length it is over two hundred miles, although in the central part of this belt the rocks are disturbed and often hidden by the later igneous rocks of the Keweenawan. It is almost always less than ten miles in width, and very often no more than two or three miles.

The stratigraphy of the Animikie rocks is nearly uniform throughout the whole extent of this belt, except where locally disturbed, as stated. In general, they are arranged in a gentle monocline, which dips south, with often a decided east-of-south tendency, at a slight angle, which perhaps averages from ten to fifteen degrees. In the northeastern part of the state the strata thus disappear beneath the Keweenawan rocks; in the western part, the continuation to the south is hidden by a great thickness of drift. Other than this uniform and slight monoclinal tilting and the accompanying disturbances, there have been no regional changes in the position of the Animikie series. There has been no folding of importance, nor even any marked development of induced slaty cleavage in the argillaceous rocks which form a great part of its thickness. The disturbances which took place between the end of the Keewatin and the beginning of the Animikie period were thus in this region incomparably greater than the changes of all succeeding time.

For present purposes the Animikie series may be divided into three chief members;—the basal quartzite, the iron-bearing member, and the upper slates.

THE PEWABIC QUARTZITE.

So far as is yet definitely known, the quartzite which is here called Pewabic lies at the base of the Animikie rocks in Minnesota. It is tolerably uniform throughout its extent, varying in texture from an extremely fine-grained variety to a very common sort, where the small pebbles of translucent quartz

average perhaps an eighth of an inch in diameter, and are very closely crowded together, and finally to a rare conglomeratic phase, in which the pebbles are still almost entirely of quartz. This conglomeratic phase is supposed to represent the extreme base.

The only change of importance which has overtaken the quartzite since its deposition has been the filling of the interstices with silica by enlargement of the grains of sand. Ordinarily, these enlargements are of crystalline quartz, like that of the original grains, and the additions have been made without any change of the crystallographic axes; but occasionally, especially near the top of the formation, specimens are met with where the filling has been made with aggregate or cryptocrystalline silica. The source of this secondary silica will be shown to be the disintegrating iron-bearing member above.

THE IRON-BEARING MEMBER.

The rocks which contain all of the ores of importance along the Mesabi range constitute a strongly marked horizon, presenting as a whole no resemblance to the quartzite member or the slate member. In places where these three most important members of the Animikie series of the iron-bearing region occur together, the boundary which separates the iron-bearing member from the others, above and below, is distinct. Its lithological characteristics will be discussed and described in detail further on.

Distribution of the Iron-Bearing Rocks.

The iron-bearing member is known to extend in Minnesota from Pokegama falls, on the Mississippi river, as far as Gunflint lake, on the Canadian boundary. From this point the Animikie series continues eastward to Pigeon point, along the international boundary, and thence into Canada, where it is best known around Thunder bay. In Minnesota the existence of the iron-bearing member is not known east of the Gunflint Lake region, where it is well shown, and where most of the observations upon it have hitherto been made. At Pigeon point it is not found, although the rocks of the Animikie series are well exposed. Neither does it seem to occur at Thunder bay, although the discovery of iron in this region, comparable with the deposits of the Minnesota part of the series, has been predicted by some Canadian geologists. But this belief seems to have been founded simply on the recogni-

tion of the Animikie series as a whole, as the rocks associated with ore deposits; and appears to be inaccurate, from failure to distinguish the iron-bearing member as the only one which contains ore in appreciable quantity. Irving,* in describing the rocks of the Thunder bay region, did not recognize the existence of the iron-bearing member. Following are extracts from his description:

"Around Thunder bay the rocks of this series, which are chiefly black slates, graywackes, argillaceous quartzites, interstratified diabase, and gabbro layers, which are many in number, and individually often have a considerable thickness, are exposed on a large scale.

"So far as it is developed along the international boundary line, the lowest layers of the Animikie series in sight are those on Gunflint lake. The highest layers are those in the vicinity of Grand Portage bay, the whole succession between these points being some thousands of feet in thickness. The iron-bearing horizon at the base of this succession is lithologically identical with that of the Penokee series of northern Wisconsin and Michigan, while the black slates, graywackes, etc., which succeed the iron-bearing horizon, are in turn the counterparts of those which form the middle and upper portions of the Penokee series."

At present, therefore, we must consider the iron-bearing member to be limited, at its western extremity, by Pokegama falls, on the Mississippi river, and on the east, by the vicinity of Gunflint lake. It is found for some slight distance west of the Mississippi river;† and at its eastern limit it is well-developed both on the American and the Canadian shores of Gunflint lake. Its length is thus nearly one hundred and fifty miles.

Stratigraphic Relations.

The iron-bearing member occupies a definite and constant position with regard to the other members of the Animikie series. From Pokegama falls to the region of the Embarras lakes, it is for the greater distance known to rest directly upon the quartzite, and to be overlaid by the slates. In this region these three members are persistent and constant in their relations, and they are not disturbed or modified by any other rocks. From the Embarras lakes region to the vicinity of Gunflint lake the relations of the strata have not well been made out, owing to the confusion arising from the presence of the great gabbro of the Keweenaw, which conceals the Anim-

*U. S. Geol. Survey, Seventh Annual Report, pp. 420-422; on the Classification of the Early Cambrian and pre-Cambrian Formations, by R. D. Irving. Quoted in Tenth Annual Report, p. 403; The Penokee Iron-bearing Series of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise.

†Twentieth Ann. Rep.; Minn. Geol. and Nat. Hist. Survey, p. 116. The Mesabi Iron Range, by Horace V. Winchell.

ikie strata, or disturbs their positions and apparent relations. As far as can be ascertained, however, the association of the iron-bearing member with the other two grand divisions of the series, especially with the underlying quartzite, do not strictly hold for this region. In township 60 north, range 13 west, section 13, it has been found resting directly upon the granite of the Giant's range. A drill-hole sunk under the direction of the Longyear Company in this place passed through one hundred and ninety feet of hard "jaspery taconyte" banded with ore. The bands of ore were five or six inches thick, and the iron was hard, black, and nearly always magnetic. At Gunflint lake the lower quartzite, according to Irving* and others, is not found, but the iron-bearing member lies directly upon the unconformable schists of the Keewatin. A few miles west of Gunflint lake it was found to lie on the granite, as reported by the professors Winchell.† Further east than this its relation is not known since it does not appear in the horizon of rocks exposed.

Divisions of the Mesabi Iron Range.

It will thus be seen that the Animikie of Minnesota may be separated into three geographical regions, of about equal length and marked by differences sufficiently great to make a division desirable. The first division, which we may call the Western Mesabi region, extends from the Mississippi river to the neighborhood east of the Embarras lakes. The second division, which may be called the Eastern Mesabi region, extends from the vicinity of the Embarras lakes to the neighborhood lying south and west of Gunflint lake. The third division, which may be called the International Boundary region, extends from Gunflint lake eastward into Canada.

Broadly speaking, the Western Mesabi region is characterized by the persistent occurrence of the three main divisions of the Animikie as described for Minnesota, and the absence of later disturbing rocks like the gabbro and traps of the Keweenawan. The Eastern Mesabi region is marked chiefly by the predominant influence of the traps and gabbros above mentioned, together with the other features, which will be shown to be probably the direct result of their invasion: the obscuring of the true stratigraphy; the predominant magnetic condition of the iron, and the more crystalline state of the accompanying

*Loc. cit.

†Sixteenth Ann. Rept., pp. 80, 266-268.

silica; and the absence of iron, so far as yet shown, in bodies large enough for profitable mining. This region is also marked by the subordination in importance of the lower quartzite, and its final disappearance. The International Boundary region also is characterized by the constant occurrence of igneous rocks within the series, but in less quantity, and occasioning less confusion than on the Eastern Mesabi; by the subordination in importance of the iron-bearing member, and the great development of the upper slate division. The Mesabi iron-bearing formation is thus separated into two divisions, the Eastern and Western Mesabi.

For the reasons above mentioned, the Western Mesabi offers the most attractive field for study upon the causes and conditions governing the formation of the great ore deposits which lend the chief economic interest to this series. Not only are the strata little disturbed and the rocks less altered than in any other part of the Animikie series of Minnesota or even than the rocks of any other of the iron regions of Lake Superior, but it is here that the formation of ore has been accomplished on the most magnificent scale. Within this district all of the paying mines and promising explorations so far discovered on the Mesabi are located; and in the amount and quality of the ore already developed, it compares favorably with the richest of the older ranges.

The known ore-bearing district at the present time is marked, in its highest development, by the Hale mine on the east, situated in the northeast corner of T. 58-16, and on the west by the Mesabi Chief mine, situated in the eastern part of section 23, of T. 57-22. East of the Hale no paying mines have been developed, and west of the Mesabi Chief but one mine is found, which, however, is one of the oldest on the range,—the Diamond, in T. 56-24. While it is probable that other bodies of ore will be discovered outside of these limits, especially in the region between the Mesabi Chief and the Mississippi, yet it is here that at the present time there are the greatest opportunities for acquaintance with the phenomena of the occurrence of ore. In the course of the explorations for iron within this area many hundred test-pits have been sunk, which serve in the place of outcrops and are of the greatest value to the geologist. It is in this district that most of the field work, the results of which are embodied in the present report, has been done; and the specimens which have served for laboratory study, and on which many of the conclusions are based, have been collected from the same region.

Thickness of the Iron-Bearing Member.

On the Western Mesabi the iron-bearing member is exposed in a strip which varies in width from half a mile or less up to two or three miles. In the narrowest parts the dip is frequently as great, locally at least, as thirty degrees. The most usual width is about one mile, and here the dip averages about ten degrees. The wider strips always occur in districts where the dip is on the average very slight. So we may estimate the thickness of the member as between 500 and 1,000 feet, with an average of about 800 feet. In several places, as in the basin of Embarras lake and that before mentioned in T. 60-13, drill holes have passed through nearly 200 feet of the iron-bearing rock. In the drilling at Embarras lake, the bottom of the formation was not reached, but in the case last mentioned the thickness represented the whole extent of the member in that place.

THE UPPER SLATES.

Above the iron-bearing member lies a series of fine-grained detrital rocks, of uncertain but probably great thickness. So far as the Minnesota territory is concerned they are at the top of the Animikie. These slates consist mainly of siliceous materials which are apparently derived from the erosion of the Keewatin rocks. There is, however, at least one marked exception to this in the lowest horizon, which lies directly upon the iron-bearing rocks. This horizon is, when least changed, an impure limestone; and it seems to be nearly continuous over a large part of the Western Mesabi.

A typical locality of this limestone is found in the pit on the south side of the road between Virginia and Mountain Iron, in the northwest of the northeast quarter of section 7, T. 58-17. This is dark gray in color, and shows an apparently original bedded structure. Specimen 76 is from this locality. The alternating layers are of different shades of gray. The rock effervesces freely with cold dilute hydrochloric acid. Under the microscope, the structure is seen to be that of an impure, little-altered limestone, consisting mainly of grains of calcite, very small, but of nearly uniform size, with which are intermixed chloritic material and iron-oxide dust. Scattering fragmental grains of quartz are also found.

In other parts of the field this calcareous layer has undergone important modifications, for, while it still remains a carbonate, yet the original calcium has been replaced, to a

greater or less extent, by other bases. Thus, near the contact between this layer and the iron-bearing series, in section 4, T. 58-16, the rock, which is seen to be identical in structure with section 76, under the microscope, is found by the analysis to have been almost completely dolomitized. This rock is described as 53-2, in the chapter on the microscopic examinations of thin sections, and the analysis of an impure portion of it is there given. In the specimen analyzed, which was obviously greatly more impure than that examined under the microscope, the remaining carbonate is seen to be almost wholly magnesite, while the ferruginous impurities have increased, owing to the immediate proximity of the rocks of the iron-bearing member, till they form the larger part of the rock.

In other parts of the field this calcareous layer seems to have undergone a ferration. This may also be ascribed to the influence of the solutions derived from the iron-bearing member, which in many places happens to lie topographically above it. Where this ferrated limestone is found, the contact between the upper slates and the iron-bearing rocks cannot be distinctly located; for the rock has not only become ferrated, but in some degree silicified; and so its structure is hardly distinguishable from some of the phases of the iron-bearing member. An example of this class of ferrated slaty rocks is specimen 112, from the northeast of the southeast of section 17, T. 58-19. Under the microscope this is very fine-grained, and consists of an intimate mixture of green chloritic matter and the carbonates, without observable arrangement, but having, on account of the uniform texture, a fragmental appearance. In the hand specimen this is a nearly black slate, without distinct slaty cleavage or well-marked planes of actual bedding. Little can be learned of the original nature of the rock through this microscopic study, but in structure it is nearly identical with the impure limestone of specimen 76, and therefore the carbonates seem to have altered from the condition of calcite without great change of form. An analysis of this rock was made with the following results.

ANALYSIS OF SPECIMEN 112. BY A. D. MEEDS (CHEMICAL SERIES 240).

Silica, SiO_2	23.80 per cent.
Sesquioxide of iron, Fe_2O_3	5.97 " "
Protoxide of iron, FeO	32.21 " "
Alumina, Al_2O_3	7.95 " "
Lime, CaO	4.67 " "

Magnesia, MgO	5.89	"	"
Soda, Na_2O.....	.29	"	"
Potash, K_2O.....	.18	"	"
Manganese, MnO_2	trace.		
Water, H_2O	4.28	"	"
Carbon dioxide, CO_2	11.84	"	"
Loss on ignition*.....	3.35	"	"
Total	100.43		

The results of this analysis are in accord with the suggestions of the microscopic examination. A part of the carbonates still consist of the calcite which is peculiar to this horizon. None of the rocks from the undoubtedly iron-bearing series have been found upon analysis to contain more than a very small quantity of lime. Thus what is here found probably represents the residue of the original limestone; the amount of magnesia represents the effects of the dolomitization, as represented in specimen 53-2, while the majority of the rock has been ferrated and changed to siderite. Two other important points of difference between this rock and the rocks of the iron-bearing member which have been analyzed suggest themselves. The first is the large amount of residual organic matter, in which respect this is identical with 53-2. The second is the presence of a trace of manganese. In none of the analyses of the iron-bearing rocks, save in profoundly altered phases, has even a trace of manganese been reported.

The thickness of this lowest and typically calcareous layer of the upper slates is not great; it grades gradually into the siliceous slates above, and the thickness may be estimated as between ten and fifty feet, varying in different localities. So far as is known on the Western Mesabi the slates above this are uniformly siliceous.

THE TILTING OF THE ANIMIKIE.

It has been stated that the only important disturbance which has befallen the Animikie strata since their deposition is the monoclinal tilting. There is a slight wrinkling of the strata into gentle undulations, and some accompanying faulting, but these phenomena seem to be connected, and may be provisionally assigned to a single period of disturbance.

It is probable that there is some connection between this disturbance and the igneous rocks which belong to the Kewee-

*Loss on ignition above the amount of H_2O and CO_2 probably represents organic matter.

nawan. Upon the middle part of the Mesabi in Minnesota these rocks have cut across the belt of Animikie strata, and thus in many places there results great change of position, steep dips and confusion of stratigraphy. Going east the angle of the dip almost steadily diminishes, the rocks at Thunder bay being often nearly horizontal.* To the west the same thing happens, the dip growing less as the distance from the central area, and in this case from the whole Keweenawan region, increases. Over the greater part of this district the direction of the dip is southward, or southeastward. In the region immediately west of the Keweenawan area there has been some slight faulting and folding, but this disturbance seems to die out as the distance from the igneous rocks increases. It is probable, then, that the weight of the Keweenawan rocks has produced a sinking of the area south of the Animikie, and that this has produced the tilting. The process of subsidence was probably slow, and was not accomplished until later Keweenawan or post-Keweenawan time, for in many places the Keweenawan rocks themselves are tilted in the same direction as are the Animikie strata, and so have participated in the movement.

*U. S. Geol. Survey, 7th Ann. Rep., pp. 420-422. On the Classification of the Early Cambrian and Pre-Cambrian Formations; by R. D. Irving.

CHAPTER II.

MINOR STRATIGRAPHY OF THE WESTERN MESABI.

The Animikie series of the iron region shows a freedom from disturbance by outside dynamic forces that is wonderful, considering the great age of the strata. The general structure of a gentle monocline is often quite undisturbed, even by slight variations; and when these modifications occur, they are generally of no great importance.

TOPOGRAPHY.

On the western part of the range the topography is least bold. Here the rugged elevation of the Giant's Range hills further east is softened down to a gentle slope, the summit of which, forming the divide as before, is often scarcely to be recognized, save from the course of the sluggish streams. Here the effect of the different underlying rocks on the topography is not great, and the change from one formation to another is marked by no sharp changes in the surface features. The highest point in the divide is not always strictly in the granite area, although it maintains itself in that neighborhood. Thus, where the divide crosses the southeast corner of T. 58-21, the summit is marked by a ridge of the quartzite, and at the very highest point of this ridge, which is in sec. 35, and is somewhat over 1,700 feet above the sea, this contour line includes a part of the iron-bearing member itself.

The dip of the Animikie strata in this region is very gentle, often seeming to the eye to be nearly flat. As a consequence of this the iron-bearing member occupies a more uniformly broad strip than it does further east, and, mainly by reason of the more even erosion, the quartzite comes to the surface in a

continuous strip, lying between the iron-bearing member and the granite. This strip is tolerably uniform through townships 57-21, 58-21, and to the center of T. 58-20. Here it narrows to a wedge and disappears, save for a local reappearance here and there further east, from under the overlapping iron-bearing member. At this point the summit of the divide definitely passes into the granite area; the hills become steep, and are strongly contrasted with the even slope of the Animikie rocks to the south. From here to the southern part of T. 59-18, the iron-bearing member generally abuts directly at the surface against the granite, the quartzite appearing only in occasional patches. Then the Keewatin schists come in between the granite and the Animikie rocks, and continue as an important feature of the geology of the range as far as the eastern limit of the Western Mesabi. Against this area of Keewatin schist the iron formation often rests.* This is seen not only in the field, from plotting of outcrops, but is proven by test-pits, as at the Hale mine and vicinity.

MINOR STRATIGRAPHY IN RANGES 18-21.

As we go east the exposed width of the iron belt shows a gradual decrease. Through ranges 21, 20, 19 and 18, the average width is probably not far from two miles. In T. 58-17 the average is between a mile and a mile and a half, and on the western side of the township it is not more than a mile. As the belt passes into township 58-16 it becomes still narrower, so that on the whole it is perhaps not more than three-quarters of a mile wide. At the extreme eastern end, at the Hale mine and vicinity, the width is probably less than half a mile in places.

This diminution in width of the iron-bearing member in ranges 16 and 17 is attended by other striking differences which make a minor stratigraphical distinction between this district and that comprised within ranges 18 to 21 inclusive, which has just been described. The structure in this latter region may be summed up as a uniform, gently sloping monocline, with, so far as yet made out, few irregularities of any importance.

*Twentieth Annual Report Minnesota Geological Survey, p. 160.

MINOR STRATIGRAPHY IN RANGES 17 AND 16.

The chief irregularity is to be noted in T. 58-17, 59-17, 58-16, 59 16, and somewhat in 57-17. For nearly all the length of the Western Mesabi, the contact of the granite and of the older schists with the Animikie rocks, runs slightly north of east; and though there are slight swings and variations, yet these are never abrupt, and the angle between the extremes of trend is probably not less than 30° . This uniform trend, which probably averages about N. 70° E., conforms with the general course of the Giant's range granite, with the planes of schistosity of the Keewatin rocks, and with the trend of the Giant's range divide. It obtains as far east as range 17, and the eastern part of range 18.

Following its regular north-of-east trend, the line of contact passes into township 59 in the extreme southeastern corner of T. 59-19. About the middle of T. 59-18 it turns, and runs nearly due east. Passing into T. 59-17 it turns still further, and for the first time begins to run south of east. Thus the contact between the Keewatin schists and the iron-bearing member crosses into township 58 again, on the line between sec. 34, T. 59-17, and sec. 3, T. 58-17. From here it runs due south for a mile and a half, through sections 3 and 10; it then turns and runs nearly due southwest for over two miles to the south line of section 20; then due south again, through sections 29 and 32, for over two miles, to the township line between 58 and 57, and into the northern part of sec. 5, T. 57-17. At this point it describes a large angle, and begins to pursue an almost due northeast course again. It keeps upon this with uniformity for some distance, crossing into T. 58-17 again at the southeast corner of section 33, and passing through sections 33, 27, 23, and 13, into T. 58-16; here it passes through sections 18, 7, 8, 5 and 4, to the northeast corner of 4, very near the boundary line between 58-16 and 59-16. At this point it turns again and runs east, with an increasing tendency to a north-of-east trend, along the northern border of 58-16. After this it resumes the normal north-of-east course.

It will thus be seen that the regular E. N. E. trend of the contact between the Animikie and the older rocks, and of the course of the iron belt, is broken abruptly in ranges 16 and 17, by two local lines of trend, which have no relation to the usual line, and yet are persistent for seven or eight miles. Of these the more western line is the more variable in direction, but has

a general course of N. N. E., thus making an angle of about forty-five degrees with the normal trend; while the more eastern has a more uniform course of N. E., making an angle of about twenty-five degrees with the normal trend; locally, however, the parts of these lines make right angles with each other. The two extraordinary lines are in some places nearly parallel, but in general converge towards the south, so that they meet in the northern part of T. 57-17.

This break of trend is also marked by a corresponding break in the topography. In the most of the iron belt, the contour lines, marking the southern slope of the divide, have a general north-of-east course; but here they swing around and follow the course of the extraordinary lines of contact. The area included between these converging lines becomes much higher, not only than the immediately adjoining country, but also than any other part of the Giant's range. The elevation of the highest points of the divide on the Western Mesabi, from ranges 16 to 21, outside of these lines, scarcely varies more than one hundred feet, and even these changes are not abrupt, but rather gradual. The highest contour line in range 21, occurring in Ts. 57-21 and 58-21, is 1,700 feet. This marks the greatest elevation for the greater part of range 20 also. On the line between 20 and 19, the elevation rises to 1,800, and maintains this height up to the more western of the two lines which have been indicated, with the exception of a small area in sec. 26, T. 59-18, which falls within the 1,850 line. To the east of the eastern line, the same observation holds good, the greatest elevation being in T. 59-16, and is marked by the 1,750 foot contour. But in the area comprised between the two extraordinary lines, the elevation rises, in T. 58-17, secs. 20 and 21, to over 1,900 feet, and in secs. 28 and 33, over 1,950, and in one place nearly to 2,000 feet. This is 150 feet higher than the highest point on the range outside of this area. These hills form a striking contrast with the surrounding country which lies south and just outside this line. From the section line, between 28 and 33, the elevation drops in a mile and a half to a uniform plain of 1,450 feet, a difference of 550 feet for the two sides of the dividing line of contact.

This break in the uniformity of the topography marks also the area included between these contact lines when they are produced to the north, past the point where they begin to swing around to the normal direction; and the area where the divergence disappears is also that of the return to the normal

topography. That part of the granite belt which lies within these lines constitutes by far the highest land of the Western Mesabi region. In Secs. 28, 59-17, granite hills rise to the height of 2,150 feet above the sea. Just west of this hill is a valley, about a mile broad, where the elevation for some distance is not more than 1,600 feet. In this valley lies the prolongation of the western of the two lines. On the other side of the valley the land rises to 1,850 feet, which we have already noted as the highest part of the Mesabi outside of the area under consideration. Thus this area is at this point three hundred feet higher than any other part of the range. Between Secs. 35 and 36, in the same township, the elevation becomes greater than 2,000 feet, and on the line between Sec. 36, T. 59-17, and Sec. 31, T. 59-17, it is still 1,900 feet. To the east of this latter eminence lies the valley of the Pike river, which is about a mile and a half broad, and has an elevation near the river of about 1,500 feet. In this valley, and along the course of the river, lies the prolongation of the eastern of the two lines. Further east the land rises from the valley, but the highest point attained is only somewhat above 1,700 feet.

From these comparisons it is seen that this area rises from 200 to 500 feet above the highest points in the adjacent country, which lies west of the western line and east of the eastern one, and that these highest points are separated from the area by profound valleys of no great width, in which the extensions of these lines lie. For convenience this elevated region will be called the Virginia area, from the city of Virginia, which is situated near it, in T. 58-17, and is the most important town of the vicinity.

THE VIRGINIA UPLIFT.

The Virginia area encloses as its center the largest body of Keewatin rocks found on the Western Mesabi south of the granite. Indeed, its bulk is nearly twice as large as that of all the rest. Surrounded by the schists are two lenses of granite, representing the ordinary granite of the Giant's range in its more finely crystalline phases. These lenses are found nowhere on the Western Mesabi save in the Virginia area. Against this central core the rocks of the iron-bearing member lie, forming a broad fringe, and passing down under the slates on their outer edges.

The character of the Virginia area, as described, points to the suggestion that it has been brought up above the surround-

ing rocks by a process of faulting. The fault lines may be supposed to correspond roughly to the lines which limit the region geographically, and are marked by the deviation of the ordinary trend of contact and the change in the topography. They were two in number, differing in trend from 30 to 45 degrees. On the south they converged and were lost in the north part of T. 57-17, and their northern ends, beginning to diverge widely, passed up into the granite belt,—the valley of the Pike marking the course of the eastern, and the valley through which the southern part of the range line between ranges 17 and 18 passes that of the western line,—and are lost in the granite belt lying north of the divide. The faulting marked by these lines seems to have affected only the Virginia area, for east and west of this a tolerably uniform relation of the strata obtains.

Evidence of the Fault at Virginia.

In the northeast of the southeast quarter of section 8, nearly at the summit of the hill which rises steeply to the east of the town of Virginia, and along which the assumed fault-line runs, a peculiar, dark, sometimes flinty phase of the iron-bearing member is found, forming the capping of the hill in this place. This rock is dark, sometimes nearly black. It is ordinarily extremely siliceous, and frequently presents the physical appearance of chert. In other bands it has more of the appearance of an ordinary indurated slate; in some places it is filled with small rhombic crystals of siderite, in others it shows a multitude of small concretion-like forms, which are a frequent characteristic of the rocks of the iron-bearing member, and will be fully described later. Going southwest down the slope of this hill, from the brow, this rock disappears, and in its place is found a deep and broad deposit of soft hematite. Near the foot of the hill the iron ore deposit ends, and at the foot a pit sunk reveals the same peculiar rock as at the brow of the slope. The horizontal distance between the two places is about six and seven hundred paces, and the difference in elevation at the surface about one hundred and thirty feet. The boring at the foot of the hill has gone down one hundred and fifty feet from the surface, without finding much difference in the rock, while that at the top has not penetrated far below the surface. In all points, however, the rocks from the two places are identical.

As will be shown, these special phases of the iron-bearing rocks are not certainly known to occupy any definite stratigraphical position, and do not form always continuous bodies,

extending over a large part of the formation, so that we cannot assign these two rocks to the same horizon with the certainty that we might have if the reverse were the case. On the other hand, it is certain that these phases, and especially the slaty, flinty phase, with which we are dealing, do extend over considerable areas, sometimes as much as a mile in diameter, without greatly altering their appearance, and without great intermixture of other phases. The edges of these areas, moreover, do not terminate abruptly, but grade off into other forms of the iron-bearing rocks. So we may have reason for believing that these two rocks, so much alike, and in such close neighborhood, were originally connected, forming one body, and that the rather abrupt break between them indicates, not a gradual change, but a mechanical fracture. The dip of the rock at the top of the hill seems to be very nearly level, but with a slightly western inclination; but this inclination is sufficient to account for only a small part of the difference of elevation between the rocks at the top and at the bottom of the hill.

In this case, we have here a normal fault with a vertical throw of at least three hundred feet, and an easterly offset of a thousand feet or more. The width of the offset is mainly occupied by the deposit of iron ore, and also in the midst of it, by the only deposit of manganese ore of workable dimensions known on the range.

Fault-plane and Breccia.

A few hundred paces north of here, following along our fault-line, test-pits sunk on the Lone Jack and the Missabe Mountain properties have encountered, in the midst of the soft ore, a deposit of peculiar character. This deposit has the form of a wall of no great thickness, the exact dip of which is not as yet known, and the strike of which seems to follow in a general way the strike of the slope. Test-pits sunk in this show it to be made up of many fragments of hard hematite, averaging perhaps three-quarters of an inch in diameter, enclosed in a cement of light red porous, friable, limonitic nature, mixed with finely divided siliceous stuff. In shape these fragments are often perfectly rounded, but they are usually sharply angular, and the edges of these prismoidal fragments show no traces of attrition whatever. This material was encountered in a vertical shaft for about sixty feet. Below this the shaft encountered a layer of white and red silica-kaolin,

varying in depth from a few inches to twelve feet. The origin of this substance will be explained during the consideration of the rocks of the iron-bearing member. Below this soft blue hematite is found. Other pits sunk on either side of this fragmental material encounter at once, immediately below the glacial drift, the same blue hematite, sixty feet nearer the surface.*

This phenomenon can only be satisfactorily accounted for by the supposition that it represents a breccia along a fault-plane. It has been supposed to represent a stream-eroded preglacial gorge, but, although the rounded shapes of some of the fragments suggest water-worn pebbles, yet the sharply angular forms of the larger part forbid this conclusion. The freedom of the material from foreign fragments is also another significant feature; and it is difficult to imagine a stream eroding a narrow gorge, with perpendicular walls, to the depth of at least sixty feet, and then refilling this gorge quite to the surface with a conglomerate of which the pebbles were composed only of hard hematite, and the cement mainly of soft ore. In the process of mining, this structure will probably be fully exposed, and an examination of it will be of great interest.

Ore-deposits Near Virginia.

This western line of the Virginia area is marked by a great number of extensive deposits of iron ore, which, taken together, make up what is undoubtedly the richest region of like extent on the Mesabi. The most valuable of all are perhaps those in the immediate vicinity of Virginia, which we have been discussing. Here are clustered together mines like the Franklin, the Norman, the Commodore, the Lone Jack, the Misabe Mountain, the Minnewas, and others. But all along the line, as we go south, we find equally valuable mines, such as the Iron King, the Great Northern, and the Great Western, till in section 31 we find the enormous ore body of the Adams mine and the adjacent properties. This continuous line of ore deposits certainly indicates somewhat unusual conditions, such as would follow the development of an extensive mechanical fracture along this line. The method of formation of the ore-bodies of the Mesabi, as will be seen later, is largely dependent upon such accidents for their large development, for it is by these means that the oxidizing agents which are necessary for the deposition of the iron are permitted to penetrate the

*Twentieth Annual Report, Minnesota Geological and Natural History Survey, p. 132. The Mesabi Iron Range, by Horace V. Winchell.

rocks extensively and thoroughly. The same remarks apply to the deposit of manganese ore, chiefly pyrolusite, which is found on the Moose property, on the southeast of the southeast quarter of section 8. Here in prospecting, one hundred tons of ore have been taken out, and the deposit promises to be of value. The occurrence of manganese mixed with the hematite is common in the ore of this vicinity, on other mining properties. The occurrence of comparatively pure manganese ore lying by the side of comparatively pure iron ore, moreover, is a phenomenon the explanation of which suggests a mechanical fissure. According to R. A. F. Penrose, such separation ordinarily indicates somewhat freely moving waters bearing the two minerals in solution, and free access of oxidizing agencies to secure their separate precipitation. The following quotation is from his work on manganese:*

If the waters from which the precipitation took place were moving, the iron and manganese, according to the difference in oxidability as stated above, would be laid down in different places, resulting in the formation of deposits of pure iron ore and deposits of pure manganese ore, occupying different positions along the plane of the same geologic horizon. Such occurrences are seen in the iron region of the Appalachians, where there are often found, in different places along the same ore belt, deposits of iron and deposits of manganese in positions similar with relation to the enclosing rocks.

These conditions of moving water might also cause the interstratified condition of the two ores already described in still water deposits: this would result if iron were deposited in a certain place at one time, and if later, on account of some increased facility for oxidation, iron were deposited before it reached that place, and the manganese, being less easily precipitated, were carried on and laid down upon the first deposit of iron.

These conditions would be in no way satisfied by waters slowly percolating through a porous rock, but would be amply fulfilled by waters making their way along the broken rocks of a great fault-plane.

The Eastern Limit of the Virginia Area.

The eastern line of the Virginia area is also marked by ore-deposits, but they are not so many nor so large as those of the western border. Still, in sec. 34, T. 58-17, and on the Towanda and the McKinley properties, in T. 58-16, we find deposits of value.

The Animikie rocks do not recover their uniformity, even when they are to the east of the supposed course of the fault-

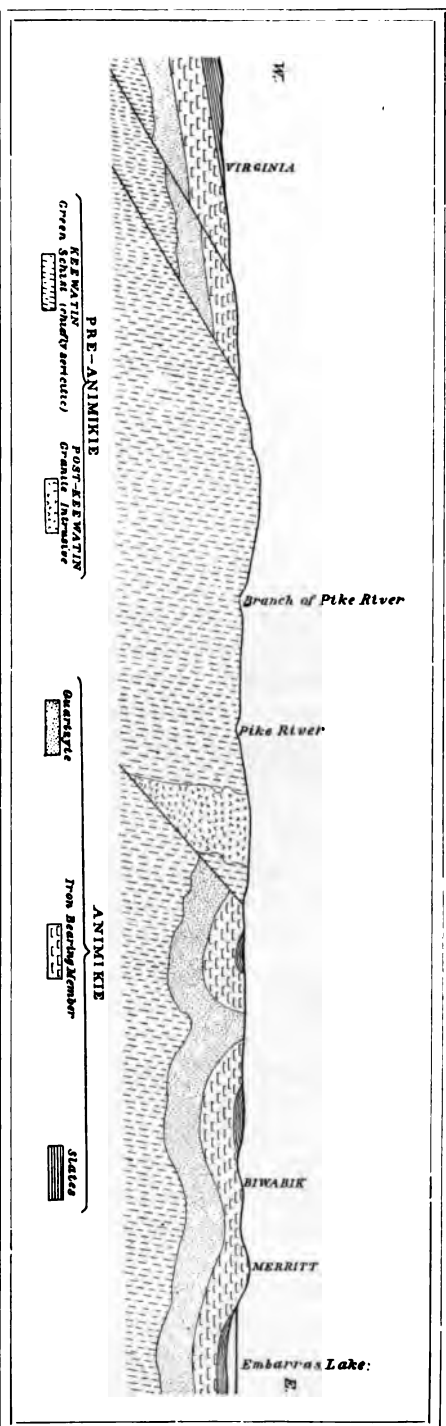
*Ann. Report, Arkansas Geological Survey, 1890. Vol. 1, p. 571.

line up the valley of the Pike. Their course in T. 58-16, from its western limits to Embarras lake, is marked by a gentle but distinct crumpling. The effect of this is to make the boundary of the iron-belt very irregular, especially on the south, as will be seen on the map. In place of the regular, broad strip of the western part of the range, there are sweeping curves, giving the belt at one place the width of over a mile, and in others near by a width of one-third of a mile or less. Attendant upon this is the wrinkling of the strata, resulting in slight elevations and corresponding depressions. An example of this is seen in sec. 4, T. 58-16, where a slight anticlinal dome is surrounded by a synclinal trough. The erosion of this structure has brought to the surface, in the centre, an area of the basal quartzite, over half a mile in diameter, from which the upper rocks fall away on all sides. The surrounding synclinal trough is represented by a ring of the upper slates, which leaves the main body, and stretches up to surround the island of quartzite. Several smaller patches of quartzite, surrounded by the iron-bearing member, are scattered throughout the length of the iron belt on the eastern line of the Virginia area, and here, also, indicate a greater disturbance of the strata than is ordinary. But in sec. 4, it is much more strongly pronounced than anywhere else; and it must be noted that through the extreme western border of the crumpled area passes the more eastern of our two fault-lines.

The disturbed district, lying between the Virginia area and the Embarras lake is, as we might expect, marked by a signal development of extensive ore-deposits. The group of mines near Biwabik and Merritt are perhaps second only to the Virginia group in importance. The explanation is the same as for the Virginia area. The disturbance of the strata was followed by freer access of percolating waters, and of oxidizing agencies with them, and thus ore-deposits were formed in favorable places.

Dip of the Animikie Strata in the Virginia Area.

On the Western Mesabi, west of the Virginia area, the dip is apt to be slight, but is almost uniformly somewhat east of south in direction. In sec. 20, T. 58-19, the ore is nearly flat; in sec. 10, 58-19, it dips about 25° S. E. This dip is probably only local. At Mountain Iron the ore dips almost imperceptibly to the southeast; in sec. 6, 58-17, it is to the southeast; in a pit on section 5, same township, it is 30° S. E. This brings us to





the western limit of the Virginia area. Once across this line there is a marked divergence. At Virginia, as seen in the rock-cut at the Ohio mine, the dip is seen for the first time to be to the west. On the cliffs of iron-bearing rock between secs. 20 and 29, T. 58-17, the rocks seem to lie horizontally. At the Adams mine the dip is slightly south, as it is in sec. 5, T. 57-17. On the eastern side of the Virginia area it again becomes southeast. At a shaft of the Towanda near McKinley, the dip is nearly 45° S. At Iron Cliff, sec. 36, 59-17, the rock appears to be usually horizontal, although locally it dips 30° S. E. In the area between the Virginia area and the Embarras lakes it is still south and southeast, although the dips are rather steeper than to the west of the Virginia area, owing to the crumpling. On the Chicago property, in sec. 4, T. 58-16, the dip is about 30° S.; at the Biwabik mine the ore dips 30° S.; at the Hale it is in places as much as 45° S.

The dips as given are taken from the iron-bearing member, and refer to the banded and bedded structure, when present; or from the horizontal parting or slaty cleavage which is developed parallel to this banding and bedding. No one of these features, however, was possessed by the rock in its original condition, as will be shown later, and so the differences of position cannot be taken to mean actual differences in the positions of the rocks, without some hesitation. It will be shown that the banding and other structures which roughly simulate stratification have been developed in planes which correspond roughly, as a rule, to the position of the overlying and underlying strata, thus giving the impression of conformable stratification; but it will be shown that tensions have been developed in the iron-bearing member, resulting in folding, and changes in the direction and angle of dip, which did not extend to the adjacent strata. So, unless we assume that this banding and cleavage from which we have taken our dips was developed at about the same time, and represents nearly the actual relation of the rocks at the present time, they are of little value. If we do assume this, then the slight westward dip on the western border of the Virginia area, as contrasted with the uniform south and southeast dip of the rocks on the rest of the range, indicates a disturbance, not great enough for a fold, but such as we might expect along a fault-line.

Concerning the nature of the fault-line on the eastern limit of the Virginia area, we do not know, but two circumstances indicate that it may have been a reverse fault, and so was nearly

parallel to the plane, as well as the trend, of the western fault. The first is the constantly narrower width of the iron-bearing belt on the eastern side of the area as compared with the western side. This difference may be estimated as on the average between 500 and 1,000 paces. Had the eastern fault been normal, like the western, there should be a strip of nearly equal width on both sides, while if the eastern were a reverse fault there would result from the overlapping the diminution of the width of the belt that actually exists. The second circumstance is the crumpling that is shown east of the eastern fault line, especially in its immediate vicinity, as contrasted with the total freedom of disturbance west, and in the vicinity of the western line. This shows that in both cases the thrust was in the same direction, towards the east. Had both faults been normal, there need not have resulted any great disturbance outside of the faulted area, on either side, and what folding took place would be in the faulted area itself; but with a reverse fault on the eastern border, the eastern thrust of the whole body of the faulted area would produce the disturbance in the adjacent rocks that we find.

SUMMARY.

The Virginia area has been faulted up from the main body of rocks, and thrust in a southeasterly direction. The two fault-planes that limit this area are roughly parallel, both in trend and hade, for a considerable distance. In the south, however, they converge so as to meet, and in the north they diverge and are lost. The upthrow has been probably not less than 500 feet, and the offset to the southeast between 500 and 1,000 feet. The movement caused the slight crumpling of the strata immediately to the east of the area. Along these fault-planes, but especially along the line of the normal fault, extensive iron-ore deposits have been developed. (See Plate II.)

DATE OF THE FAULT.

The faulting of the Virginia area and the crumpling of the strata east of it having been shown to be probably of the same age and caused by the same force. We may suppose, pending evidence to the contrary, that the slight tilting of the less disturbed Animikie strata was accomplished at the same period. The Keweenawan has already been suggested as the age of this movement, and the heaping up of the Keweenawan traps and lavas as the cause. The fragments of hard hematite in the

breccia at Virginia show that at the time the faulting took place, there was already considerable iron in the rocks, and on the hypothesis (which will be shown to be correct) that none of the iron existed in the original rocks in the condition of massive hematite, the concentration of this indicates the lapse of a considerable period of time. But the formation of the great deposits of soft ore, considered as dependent on and subsequent to the faulting, shows what an immense time has elapsed since that accident. This is indefinite, but it does not militate against the supposition that the Keweenawan was the period of disturbance.

CHAPTER III.

MACROSCOPIC STUDY OF THE ROCKS OF THE IRON-BEARING MEMBER.

Although the iron-bearing member is a unit in all respects, yet no description can be framed that will apply to all of the phases of its rocks. In appearance, in habit, in structure, and in chemical composition, they vary within the widest limits. So unlike are the different phases that they have generally been taken to represent different horizons. These conclusions have been based on the observations of a large body made up with some uniformity of a single phase; in which case the connection with another large body of a totally different phase does not at first seem apparent. In places these bodies attain considerable size, if conditions are favorable, and the diameter of the largest may be perhaps about a mile. Such bodies, representing only closely allied phases, are scattered all over the iron-bearing belt.

These large accumulations, however, form only a small part of the entire bulk of the rocks. Through the greater part the different phases are found more closely associated. A test-pit may within a few feet pass through representatives of all the important varieties of the rock, and a single hand-specimen may comprise half a dozen distinct and widely differing phases. It is when the rocks are thus closely associated that the true relationship of one type to another may be successfully studied, and by comparison of these types of which the relation has been worked out with the larger, isolated, less varied bodies, these latter may with certainty be identified, and put in their true positions as regards one another.

The study of the hand-specimens brings out the fact that the specimens are not so hopelessly multitudinous as first seems; that specimens may exist in many different localities which are in every respect identical; and that an enumeration and a classi-

fication of the different phases is very possible. It also brings out the important fact that while the phases which are mostly strongly contrasted with one another frequently occur in close proximity, yet oftener the changes are not so abrupt, and one phase may be seen passing into another by an easy transition.

With a view to assigning each of the different phases to a definite type, more than two hundred specimens, collected in the field with this special object in view, were examined, and the phases described by their outward appearance, with no microscopic or chemical aid. The result was as anticipated by observations in the field. Many of the types thus observed and described differ but slightly from one another, yet are described separately in order that the list may be full, and that there may be no danger of error from an erroneous identification of types, which, while they resemble each other, may yet have a different origin. For example, the different forms of iron ore are described as six types,—magnetite, hard crystalline hematite, friable granular crystalline hematite, earthy hematite, hard limonite, and earthy limonite or göthite. This elaboration is hardly greater than that used in describing the other types, and every variety found within the iron formation is thus described. Yet it was found that these types, as thus described, easily fell under about thirty heads. The list as worked out is given below, without any attempt to arrange the types in any order, for that order was worked out by subsequent comparisons, which will be described later. 'So any application of this would be premature, and would obscure the process of investigation as actually conducted.

PHASES OF THE IRON-BEARING ROCK.

1. Color dark gray, finely mottled with light gray. Luster mottled, vitreous and metallic. Texture granular. Fracture irregular. Heavy.

2., Color light gray, mottled with dark. Luster mottled, vitreous, metallic, and earthy. Texture granular, sometimes porous. Fracture irregular. An indistinct rough parallel parting. Specific gravity medium.

3. Color dark gray. Streak gray. Hard. Texture fine and compact. Luster metallic. Heavy. *Magnetite*.

4. Color light gray or pink. Luster vitreous to earthy. Texture porous and friable.

6. Dark brown. Friable, often hardly cohering. Grains crystalline, non-magnetic. Luster metallic. *Granular hematite*.

7. Color brown. Luster metallic. Hard; non-magnetic; texture close and compact. *Hard hematite.*

8. Color yellow. Friable; earthy. Limonite or göthite.

10. Brown, yellow, red or gray. Luster vitreous, (sometimes earthy). Hard; texture fine and compact. Fracture conchoidal.

12. Gray or white powder. Very fine-grained and friable.

13. Color blue, brown or red. Luster earthy to metallic. Texture powdery. Feel greasy or granular. Grains hardly or not at all cohesive. *Earthy hematite.*

14. Dark gray or green. Fracture conchoidal; luster vitreous; very hard. *Chert.*

15. Fine gray or green siliceous ground, mottled with soft spots, white and red.

16. Like 15 in structure, but with ground colored dark red, brown or yellow, and mottled with red or dark gray.

17. Color green or gray, well-developed slaty cleavage. Lustre earthy to silky. Medium hard; irregular fracture.

18. Like 17, but heavier, darker, and with metallic luster.

19. Color green, gray, brown, or red. Fracture irregular. Luster earthy to sub-vitreous. In texture fine-grained and compact; moderately soft, and cohesive.

20. Color red or brown. Cleavage well-developed. Luster metallic. Heavy. Is like 18, but contains more iron. *Hematite slate.*

21. Color white, red, gray, or black. Resembles somewhat 10, but as vitreous, frosty luster, and is harder. "*Jasper.*"

22. Color green; gray, white, or red. Luster earthy. Soft; mottled with white or red spots. Resembles a clastic rock.

23. Is like 16, structurally, but has a light green ground, mottled with black.

24. Is like 23 or 16, but has soft white ground, mottled with red.

25. Any color—black, white, green, gray, red, yellow, etc. Passes directly into 12. Soft; luster earthy; brittle. Cleavage very well developed. "*Slates.*"

26. Any color. Luster vitreous. Fracture granular. Hard; appears homogeneous to the naked eye.

27. Derived from 16 by leaching. Red. Regular hollow pores have been formed by the dissolution of the red spots of 16. Resembles 2.

28. Hard limonite. Compact.

29. Color green or gray, faintly mottled with lighter spots. Fracture irregular; luster vitreous; texture granular.

30. Color red-brown. Luster vitreous to pearly; structure crystalline.

31. Color green. Luster pearly. Fracture irregular. Is mottled like 22.

32. Color green; fracture irregular; luster earthy to vitreous; texture granular. Bears a general resemblance to 29.

It will be seen that these classes are so connected that they easily fall into a few larger divisions, which suggest themselves; thus Nos. 1, 2, 15, 16, 22, 23, 24, 27, 29 and 31 are all spotted cherty rocks, much resembling one another; 17, 18, 20 and 25 are all fine-grained slaty rocks; 10, 14 and 21 are fine-grained unspotted rocks, consisting almost entirely of silica; 4, 12 are light, porous and pulverulent; 32 is a green unspotted rock, not eminently siliceous; and 3, 6, 7, 8, 13 and 28 are all ores of iron. Thus all are disposed of except 19 and 30, and the characters of these two make their relationship sufficiently clear,—the first to the group of fine-grained slaty rocks, and the latter to the group which is represented by 32.

As before said, these different phases grade into one another, ordinarily showing no dividing line; and their relation is such as generally to place it beyond a doubt that one is derived from the other. In nearly every one of the specimens examined this process of change was clearly shown. The relationship of two phases in the same specimen is sometimes shown by their physical resemblance, and nearly always by the irregular, ragged nature of the boundary between them, and by the gradual change from one to another. In most cases the change is simply one of weathering, the weathered rock constituting one phase, and the fresher rock another. Then the weathered portion is found distributed along the joint-planes or other places where oxidizing agents have freest access; and the fresher rock remains within this as a ragged residuary fragment, its boundaries corroded and invaded by the weathered portion. Sometimes the weathered rock closely resembles, save for a little bleaching, the rock from which it is derived, as is the case in the transitions from one to another of many of the spotted cherty rocks; but in other cases the two phases are so entirely different that their relationship would with difficulty be established, were it not for their association. An example of this is the decomposition of a fine-grained dark, gray chert to a light, banded pulverulent rock, often quite white in color. This

change may be frequently observed. In this case not only the total change in color and texture, but also the banded appearance of the decomposition product, as contrasted with the massive structure of the primary rock, operates to destroy the resemblance between the two.

The different phases are often interbanded, sometimes quite regularly. Ordinarily, however, these bands are seen on close inspection to be by no means comparable with the alternating sedimentary layers which they have been sometimes supposed to be. In the first place, they are generally marked only by the presence of a greater or less amount of iron oxide, and in all other respects may be identical with the rest of the rock. That this iron is an impregnation may usually be plainly seen, as marked by the irregular course of the band and often by the existence of the channel by which the iron penetrated the rock, this channel being often at a considerable angle with the banding. Again, the band, after running for some little distance in a straight line, generally bends, describes a curve or even an angle, and runs in a different direction; or again, it forks, and the branches separate widely, or again converge and meet; or the band may stop suddenly and entirely. It is rare that in any specimen from the rocks of the iron-bearing member the evidence against any sedimentary nature of the banding is not clear; and in these rare cases the true secondary nature may always be discovered by study of other specimens from the same place.

The relative age of the different phases, where they occur together, is usually evident. The original rock exists not only in a compact body, but also as residual fragments, large and small, surrounded by the secondary rock. The discovery of the residual fragments establishes at once the relation of the two rocks. These are angular as a rule, sometimes rounded, and their boundaries are irregular and not firmly marked. When the process is one of weathering, and the resulting rocks still resemble one another, that phase which follows the joint, cleavage or fracture planes may be taken as the secondary phase, and its appearance is usually an additional guarantee that this is the right conclusion. (See Figs. 3 to 9 inclusive.)

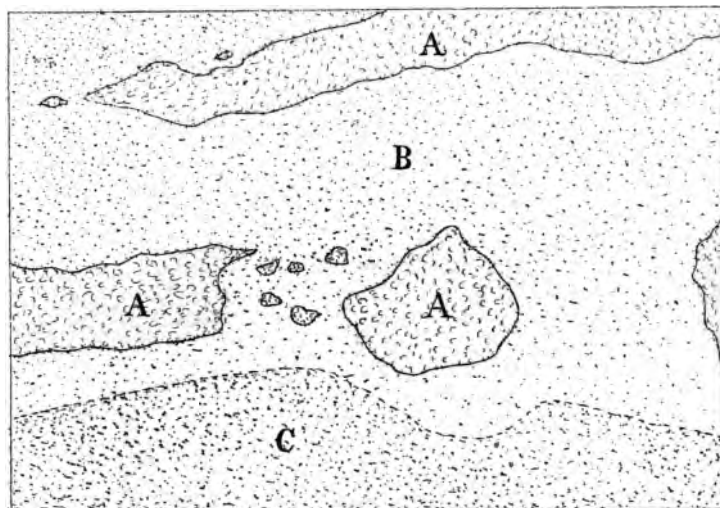


FIGURE 2.

Sketch of Specimen A, (slightly enlarged.)

A. Residual fragments of very light gray rock, of granular texture. Upon the light gray background there are numerous thickly clustering rounded bodies which are still lighter in color.

B. Harder rock, with a tendency to a conchoidal fracture and a finer texture than A. In color a nearly uniform rich brown. B is derived directly from A, chiefly by staining with iron oxide.

C. Very dark brown, highly ferruginous rock, locally passing into pure hematite. Is derived from B directly, by a continuation of the process of impregnation by iron oxide.

This specimen shows the destruction of the regular banding, by the advancing processes of change; and the formation, by division of the bands, of isolated residual patches. In the figure the former existence of two unbroken bands of the least altered rock (A) can be observed. These bands originally connected the separated fragments, but have been altered to their present state by the invasions of the altering agents. In the next stage A will entirely disappear. Finally, with greater change, B will also disappear, passing into C, which in turn may alter into some slightly differing phase.

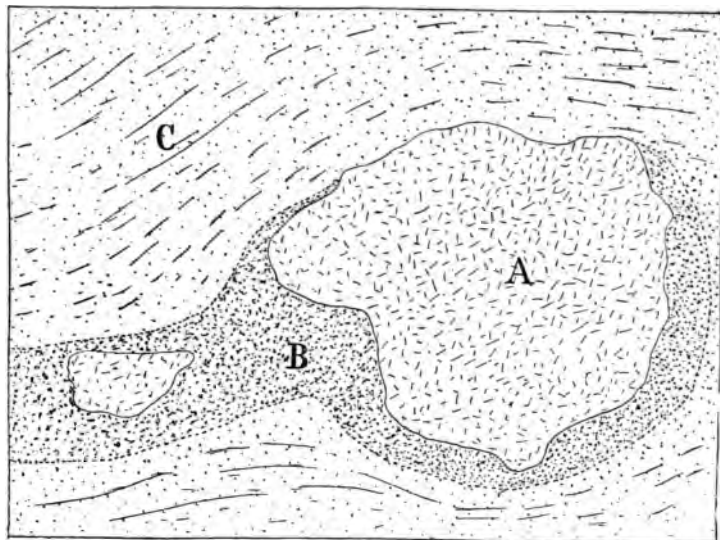


FIGURE 3.

Diagrammatic Sketch of a part of Specimen 31, (slightly enlarged).

- A. Dark gray cherty rock.
- B. Brown, hard, granular rock.
- C. Brown to nearly white, friable, granular rock, sometimes slightly banded.

This specimen shows the stages in the decomposition of a siliceous rock. A, the original rock of the three, is an impure chert. During the process of weathering this becomes brown, by oxidation of its iron. The disintegration is also shown by a change in the texture, which becomes granular, and by a loss of the smooth conchoidal fracture. This stage, represented by B, is transitional between A and the completely altered rock, which is represented by C. C is almost entirely disintegrated; is leached of most of its iron, and is rapidly approaching the condition of a residual silica powder. Here, again, it is evident that the two fragments of the original cherty rock were once connected, so as to form a single band; and the area occupied by B is that which the original material last occupied.

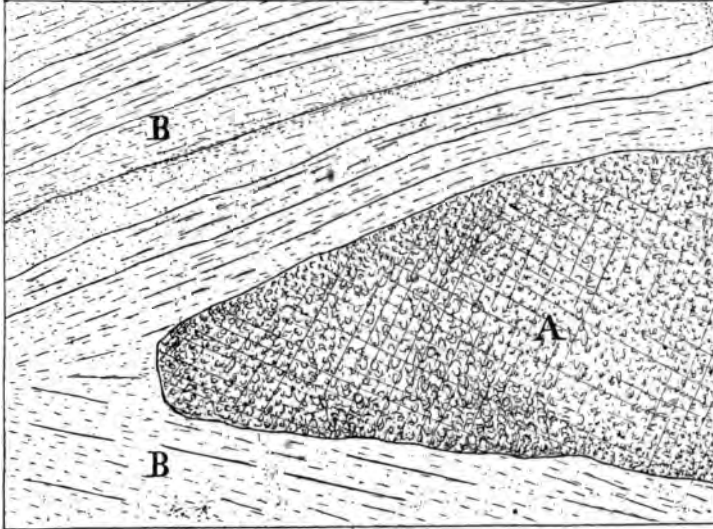


FIGURE 4.

Diagrammatic Sketch of a part of Specimen 28, (slightly enlarged).

A. Residual fragment of, red, siliceous rock; massive, with the characteristic spotted appearance, granular texture and conchoidal fracture.

B. Fissile slaty rock, banded, light and dark gray. The darker bands are highly magnetitic, the lighter ones siliceous and chloritic.

The decomposition of a hard, siliceous and ferruginous rock, to form a banded slaty rock, is well shown in this specimen. The process seems to be that of simple weathering along joint-planes; and the contraction of each successively weathered zone, due to the loss of its more soluble constituents, has produced the slate-like cleavage. The removal of iron from certain of these decomposition zones, and its concentration in others, has produced the banded appearance of the resulting rock. Most of the rock in the pit from which this specimen was taken was thus changed, and the resemblance to a somewhat altered slate is very deceptive.

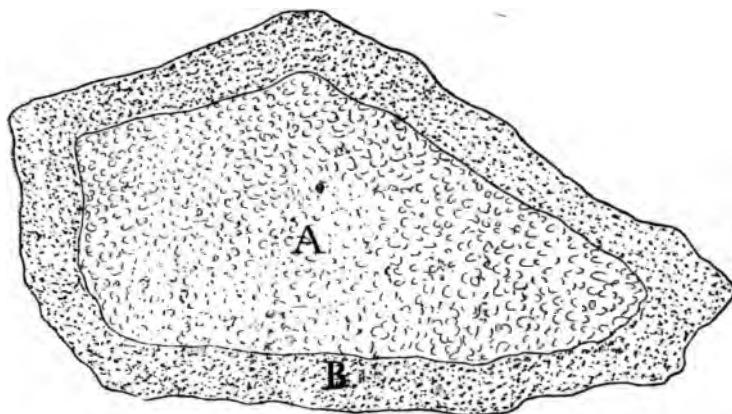


FIGURE 5.

Diagrammatic Sketch of Specimen 212, (actual size).

- A. Light gray, granular rock.
- B. Dark brown, granular rock.

This specimen shows the alteration of the original rock A to the dark brown phase B, chiefly by impregnation with iron oxide, with the attendant removal of silica. The shape of the specimen is the same as when found, and its outlines correspond to joint-planes which bounded it in its original position. Along these planes the agents of alteration entered, and penetrated the rock, progressing slowly inward. Thus a wide and well-marked border has been formed. In other specimens phases corresponding exactly to A and B are found in somewhat regular horizontal bands, alternating one with another; and in these cases the method of formation of the darker bands from the lighter must be the same as for the corresponding areas in the figure.

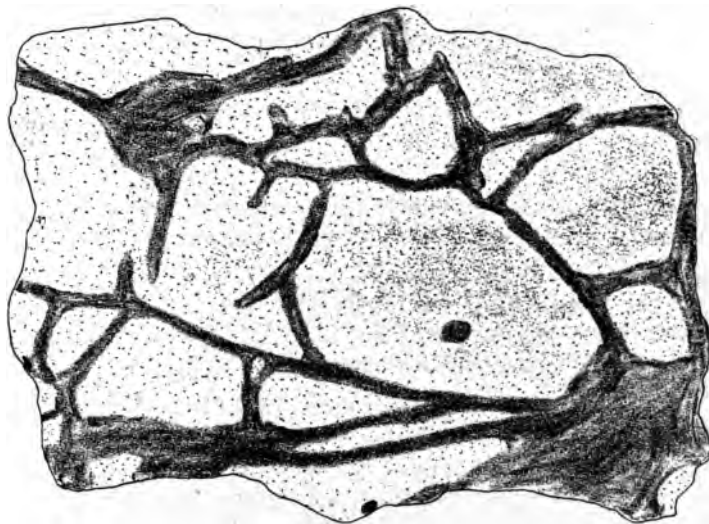


FIGURE 6.

Diagrammatic Sketch of Specimen 134, (actual size).

This sketch is made of a surface parallel to the horizontal parting or jointing of the rock. A very irregular arrangement of the darker seams is shown, and one which shows well the conditions which give rise to this structure. The lighter portions of the cut are of a light gray, granular, porous and friable rock, consisting almost entirely of silica. The dark reticulated seams are deeply stained, dark brown, with iron oxide; and often this process is carried so far that pure hematite results, especially in a narrow strip in the very centre of these darker portions. It is clear that the structure has been brought about by the infiltration of iron oxide in solution into crevices; and from the distribution of these crevices the contraction of the rock seems to have been the force which produced them.

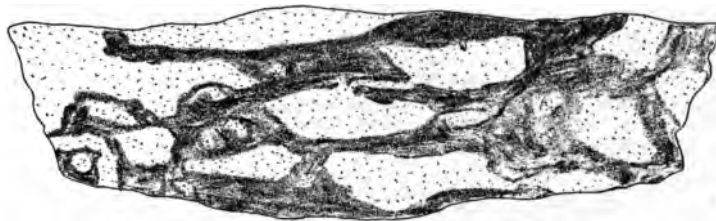


FIGURE 7.

Diagrammatic Sketch of Specimen 134, (actual size).

This is from the same specimen as figure 6, but is made at right angles to the horizontal planes of easiest division. The upper and lower outlines of this figure show the unequal course of the actual surfaces of separation. As in figure 6, the lighter parts represent porous and somewhat disintegrated siliceous rock; while the darker portions are stained by iron oxide, or are completely changed into hematite. The course of the ferruginous seams is very irregular, but the tendency to a horizontal arrangement, suggesting the banded structure which is the most usual occurrence, is very evident. The iron oxide is so distributed as to include patches of the original light-colored material; and with the continuation of the process of ferration these will be reduced in size and number, thus constituting scattered residual fragments in the midst of the highly ferruginous rock; and finally will be marked only by spots poorer in iron than the rest.

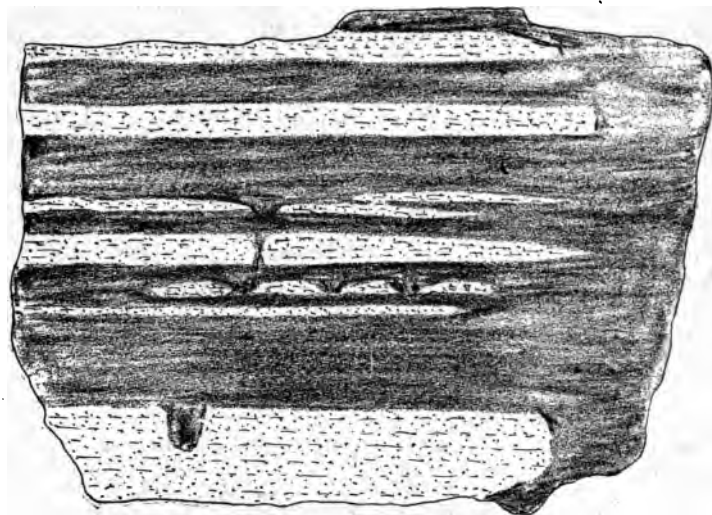


FIGURE 8.

Sketch of Specimen 148 (actual size).

The pit from which this specimen was taken contains rock which in general is beautifully banded, often without any noticeable irregularity. This specimen was selected as showing irregularities in the banding which explain the manner of its formation. The lighter parts of the cut represent a light gray, granular, porous and friable rock, with very fine banding of lighter and darker gray. The darker parts represent portions which have in general the same characters, but are harder, and dark brown in color.

That the darker portions have been produced from the lighter by deposition of iron oxide from infiltrating waters is shown by the irregularities of the banding. The right hand side of the cut represents a portion which was adjacent to a crevice, and in this vertical zone the whole rock has been stained. Most of the horizontal bands are regular and continuous, but often the channel by which the ferruginous solutions have leaked down from one band to another are shown.

For the purpose of discovering what order there was in the transition of certain phases into certain others, the specimens collected have been carefully studied in the hand specimen, and the changes noted in them tabulated, as given below. The numbers used refer to the different phases as described and numbered above:

TRANSITIONS OBSERVED IN THE HAND SPECIMENS.

<i>Spec. No.</i>	<i>Transitions of Phases.</i>	<i>Spec. No.</i>	<i>Transitions of Phases.</i>
10.	1.	70.	12.
11.	1 to 2, 2 to 3.	71.	2 to 10, 10 to 19.
12.	4 to 5 (4 is probably derived from 2.)	73.	15 to 16, 15 and 16 to 12, 16 to 10.
13.	6 to 8, 7 to 8. (Probably 7 is derived from 5, hard by.)	74.	16 to 12.
14.	32 to 3.	75.	16 to 12 and 22.
17.	29.	78.	16.
18.	9.	79.	14, finely banded white and gray. Breccia.
19.	1 to 10, 10 to 11, 1 to 12, 10 and 11 to 13. (Cavity forming.)	80.	14 to 12, 8 and 13; 14 to 17.
20.	1 to 3, 1 to 10, 10 to 12.	81.	2 to 18.
21.	14 with 10.	82.	16.
22.	10 to 2; 2 to 3, 6 and 8; 3 to 6 and 8.	83.	23.
24.	1 to 3, 3 to 7 and 13.	85.	16 to 24, 24 to 22, 22 to green and to red 25.
26.	7 to 8 and 13.	89.	19-25.
27.	15 to 16, 16 to 14, 14 to 17, 17 to 12.	90.	19-25.
28.	15 to 17, 15 to 18, 17 to 18, 15 to 12, 19 to 18.	91.	25 green, to 25 white and yellow.
29.	19 to 18, 18 to 20.	92.	19 to 25.
30.	18 to 6.	93.	14 to 10, 10 to 19.
31.	16 to 10, 10 to 19, 19 to 12, 19 to 13.	97.	21.
32.	16 to 10.	99.	Black 14, with pyrite; 20 to 6.
33.	15 to 16.	100.	16 to 6.
34.	15.	101.	25 (gray.)
35.	1 to 7 and 13.	103.	25 (gray.)
36.	1 to 7 and 13.	107.	1 to 8 and 13.
37.	?	108.	16 to 2, 16 to 1, 16 to 6 and 3, 16 to 12.
38.	?	109.	26 (26 to 27?), 27, 27 to 10.
39.	?	110.	26 (26 to 27?), 27, 27 to 10.
40.	21 to 7.	111.	16 to 27, 16 to 10, 16 to 25, 16 to 19.
41.	16.	115.	14 to 19.
42.	1 to 7.	116.	14 to 19.
43.	12.	117.	14 to 19.
53.	?	119.	19-14 to 19, 19 to 25.
64.	16 to 22, 12, 10 to 12.	120.	14 to 19, 19 to 25, 25 to 12.
65.	16 to 22, 12, 10 to 12.	121.	14 to 19, 19 to 25, 25 to 12, 25 to 5.
66.	22, 12, 10 to 12.	122.	14.
68.	16, 2, 14 to 10, 10 to 19.	123.	1 to 27, 27 to 12, 12 to 25, 25 to 7.
		124.	3 to 28.
		125.	29 to 3, red 10 to 3. Pyrite.
		126.	7 and 28, 28 to 8.

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|---|--|
| 127. 14 to 10, 10 to 19. | 160. 19 to 20. |
| 128. 29 to 15, 15 to 10, 29 to 27, 29 to 7, 10 to 12, 29 to 12. | 161. 16 to 2. |
| 129. 1, derived from 29. | 162. 7 to 8. |
| 131. 32 to 30, 30 to 4. | 164. 14 to 21. Pyrite. |
| 132. 32 to 30, 30 to 4. | 166. 16 to 14. Pyrite. |
| 133. 29 to 2, 29 to 4, 4 to 3; 3 to 7, 28 and 8. | 170. 25. |
| 134. 26 to 4, 4 to 3; 3 to 7, 28 and 8. | 171. 15 to red 10. |
| 135. 16 to 1; 1 to 3 and 8. | 185. 23 to 14-19; 14-19 to 7. |
| 136. 16 to 27, 27 to 23, 23 to 12, 23 to 3. | 204. 7 to 8 and 13. |
| 137. 31 to 3; 3 to 7 and 8. | 208. 2 to 7. |
| 138. 25. | 210. 14 to 19. |
| 143. 2 to 7. | 211. 2 to 10, 10 to 7. |
| 147. 2 to 10, 10 to 12 and 8. | 212. 2 to 5. |
| 148. 19 to 3 and 7. | 213. 10 to 7, 30. |
| 150. 2 to 10, 10 to 25. | 214. 2 to 10. |
| 151. 2 to 10, 10 to 8, 10 to 7. | 215. 2 to 7, 26 to 7. |
| 152. 25. | 216. 2 to 5. |
| 153. 25. | 217. 29 to 3. |
| 154. 18. | 219. 31 to 1, 31 to 3, 3 to 8. Pyrite. |
| 155. 14. | 218. 10 to 7, 7 to 8 and 13. |
| 156. 31 to 2, 2 to 3 and 7. | 220. 26 to 3 and 7. |
| 157. 15 to 16, 16 to 18, 18 to 20. | 221. 19-25. |
| 158. 19 to 20. | 222. 14-19-25, 14 to 19, 19 to 25. |
| 159. 15 to 16, 16 to 19, 14 to 2. | 223. 25. |
| | 225. 19 to 25. |
| | 224. 2-10. |
| | 229. 12. |
| | 230. 12. |

By collecting from this list the different changes which each rock has undergone, we may make out the following table. This shows after each phase as enumerated and described above, the phases into which it has been seen to pass by a gradual transition, the circumstances in each case observed being in general such as to show that one was derived immediately from the other.

TRANSITIONS FROM ONE PHASE INTO ANOTHER.

From Phase 1 are derived Phases 2, 3 (twice listed), 7, 8 and 13.

"	2	"	"	3 (3 times listed), 6, 8, 10 (6 times), 18, 7, and 5 (7 and 5 twice listed).
"	3	"	"	7 (4 times), 13, 28 (3 times), 8 (5 times), and 6.
"	4	"	"	5 and 3.
"	5	"	"	Nothing.
"	6	"	"	8.
"	7	"	"	8 and 13.
"	8	"	"	Nothing.
"	10	"	"	11, 13, 12 (4 times), 19 (3 times), 8 (twice), 25, 7 (3 times), and 3.
"	11	"	"	13.

From Phase 12 are derived Phases (Iron ores, by replacement).

"	13	"	"	Nothing.
"	14	"	"	17 (twice), 10 (3 times), 19 (4 times), 2, 21, 17 (twice), 12, 8, and 13.
"	15	"	"	16 (3 times), 17, 18, 12 (twice), and 10.
"	16	"	"	14, 10 (3 times), 22 (twice), 12 (4 times), 24, 6, 2, 1 (twice), 3, 27 (4 times), 25, 19 (twice), and 18.
"	17	"	"	12 and 18.
"	18	"	"	20.
"	19	"	"	18 (twice), 12, 13, 25 (7 times), and 7.
"	20	"	"	6.
"	21	"	"	7.
"	22	"	"	25.
"	23	"	"	12, 3, 14, and 19.
"	24	"	"	22.
"	25	"	"	12 (twice), 5, and 7.
"	26	"	"	4, 3, 7, and 27.
"	27	"	"	10 (twice), 12, and 23.
"	28	"	"	8.
"	29	"	"	3 (twice), 27, 7, 12, 30, 2, and 4.
"	30	"	"	4.
"	31	"	"	1 and 3.
"	32	"	"	3.

By inspection of these transitions it becomes at once apparent that there is a definite order which runs through them. This is shown by the recurrence, repeated many times, of the same change, showing that the change always takes place in a constant direction, is never reversed, and is apparently inevitable under normal conditions. At the same time each of the phases is seen to pass into so many others, and so many others are derived from it, that it is evident the process is a varied one, and protracted into a large number of stages; and again it is found that each of the phases derived in one case from a single primary rock may in other cases be derived from other primary rocks. Then if in any one of the transitions observed the derivation of one of the primary rocks from another may be established, the relation, not only of these phases, but of the phases that are derived from them, becomes at once apparent. A continuation of this process gives the relationship of all the phases to one another.

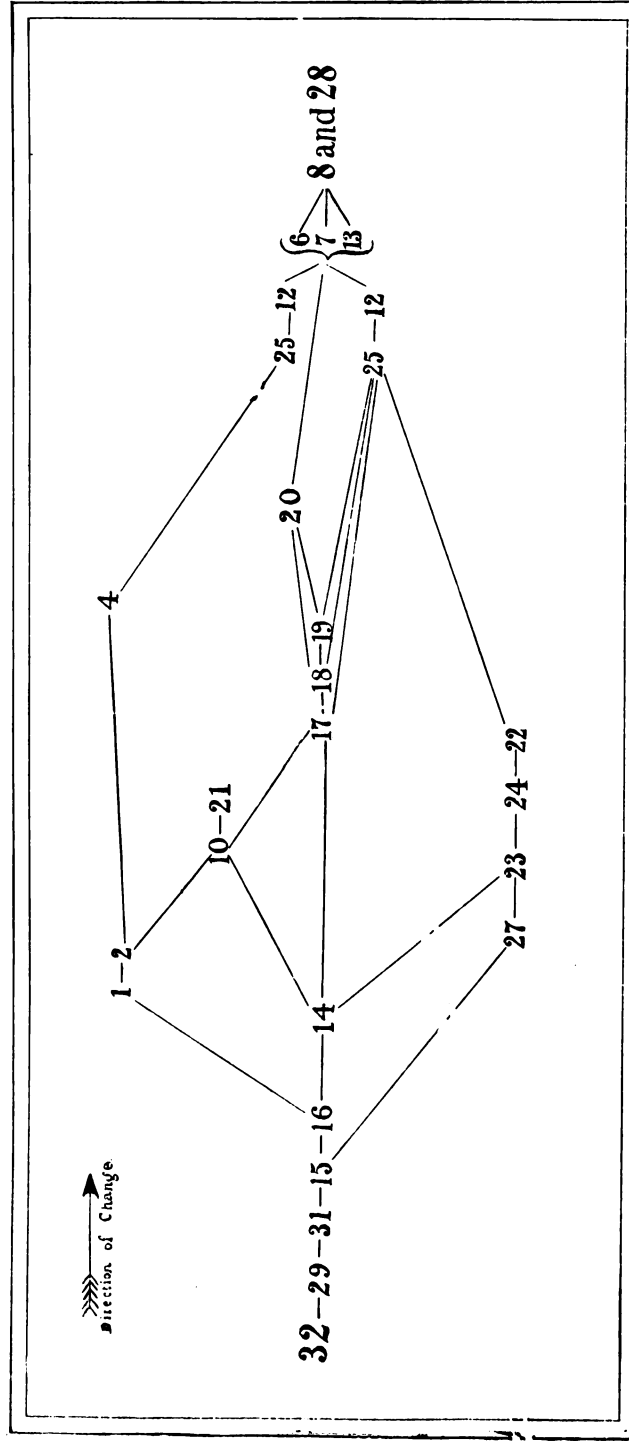
It is seen at a glance that those types from which few or no derivatives are recorded, stand near the end of the series, and, on the other hand, that types from which many others, representing as a whole a large part of the series, are repeatedly seen to be derived, stand among the results of the first stages in the process of change. This rule must be applied with cau-

tion in the first instance; for it may happen that few changes are recorded of a rock simply because it happens to be a rare type, and so the changes which actually take place in it have not been observed in the two hundred and thirty specimens studied. Still, the rule in general holds good; and the study of a larger number of specimens would entirely remove this difficulty. So phases like 5, 6, 7, 8, 11, 12, 13, 20, 25, 28, etc., probably represent the closing stages in the change; and phases like 30, 31 and 32, although few derivatives are shown for them, may yet be finally put in their rightful place near the beginning of the series by their resemblance to others which have already been put there. On the other hand, rocks like 10, 14, 16, 17 and 29 at once suggest themselves as representing those which must be placed among the first, and in this case there is no possibility of error in the classification.

By these methods the different phases are found to be related substantially as represented in the accompanying diagram. This diagram agrees almost exactly with nearly every one of the observed changes, an agreement rather remarkable, considering the possibilities for error in classifying by the physical peculiarities of the hand-specimen alone. (See Plate III.)

The process of change worked out by the method above indicated may be briefly described as follows:

A massive, granular, green rock, represented by the number 32, with often a peculiar mottled structure, as represented by 29 and 31, forms the first of the series. By a slow and gradual process of change, which is seen from the descriptions and from the specimens to be substantially a process of weathering, this rock goes through the series indicated by 27, 23, 24 and 22. In this process it becomes soft, loses its firmness and passes through various stages of color in the process of bleaching. This profoundly weathered rock which still, however, retains the mottled structure, then passes by further disintegration to a phase like 25, where the mottled structure is obliterated, and the consolidation of the resulting mass has produced a certain slaty nature. This rock may be very light in color, or it may be stained various hues by iron and other coloring agents. Further decomposition gives a scarcely coherent clay or powder, which is typically white, though, like 25, it may be stained. This is the condition of phase 12. This is the end of the decomposition process, but the powder may become strongly impregnated with iron, forming the various iron ores 7, 8, 28, 13, etc.



DIAGRAM, SHOWING THE RELATION OF THE VARIOUS PHASES OF THE IRON-BEARING ROCKS LISTED FOR THE WESTERN MESABA.

The figures refer to phases described on page 27.



The same mottled green rock gives rise to the series represented by 1, 2 and 4. Here the change is manifestly also one of decomposition, but it is much more rapid, and the leaching goes on faster than the comminution of material. The resulting rock, 4, bears a general resemblance to 25, the rock resulting from the slower and more protracted weathering, in that it is of low specific gravity, typically of light color, and is porous and friable. It differs chiefly in that the individual grains are much larger, so that the texture is granular instead of pulverulent. This coarser variety may undergo a further decomposition to a phase like 12, which is also the decomposition product of 25, or it may be directly impregnated with iron to form the iron ores. Phases 1 and 2 preserve the mottled structure, and the whole series bears a strong resemblance to the series of 27-22 inclusive, the differences appearing to consist in the different degree of access of the forces which produce weathering, in the different localities from which the specimens were taken. Phases 1, 2 and 4 are all found in one locality, where the phases of the other series do not occur; and phases 27-22 inclusive are profuse in a region which affords few representatives of the first series.

As a second chief division in the evolution of phases are the cherts, without mottled structure, and the slaty rocks. The cherts are usually slaty or banded, and pass by easy transitions into the more markedly slaty rocks. Sometimes the cherts contain scattered crystals of siderite, sometimes none. The more slaty rocks are usually characterized by a greenish color, fine texture and weathered appearance in some layers, and by the presence of a greater or less amount of iron oxide in others. These banded cherts and slates may spring from the green and massive rock, at the same point as the series before described; but they may also be derived from any point of the first series, in its less altered stages. Thus 14, which represents the pure cherts, is found to be derived from 16 in one case, and from 23 in another; 14 passes into the slaty rocks, represented by 17, 18, 19 and 20. Of these rocks those most deeply impregnated with iron pass directly into the iron ores, while the lighter, greenish varieties weather and are bleached till they pass into the type 25, and thence to 12. This last condition, represented by 25 and 12, will be seen to be identical with the last stages of decomposition of the series first described. As in the first case, of course, 12 may become impregnated with iron oxide and thus pass into the iron ores.

The hydrated oxides seem to represent the most stable form of iron under copious atmospheric agencies, and so these may properly be put at the end of our typical scheme.

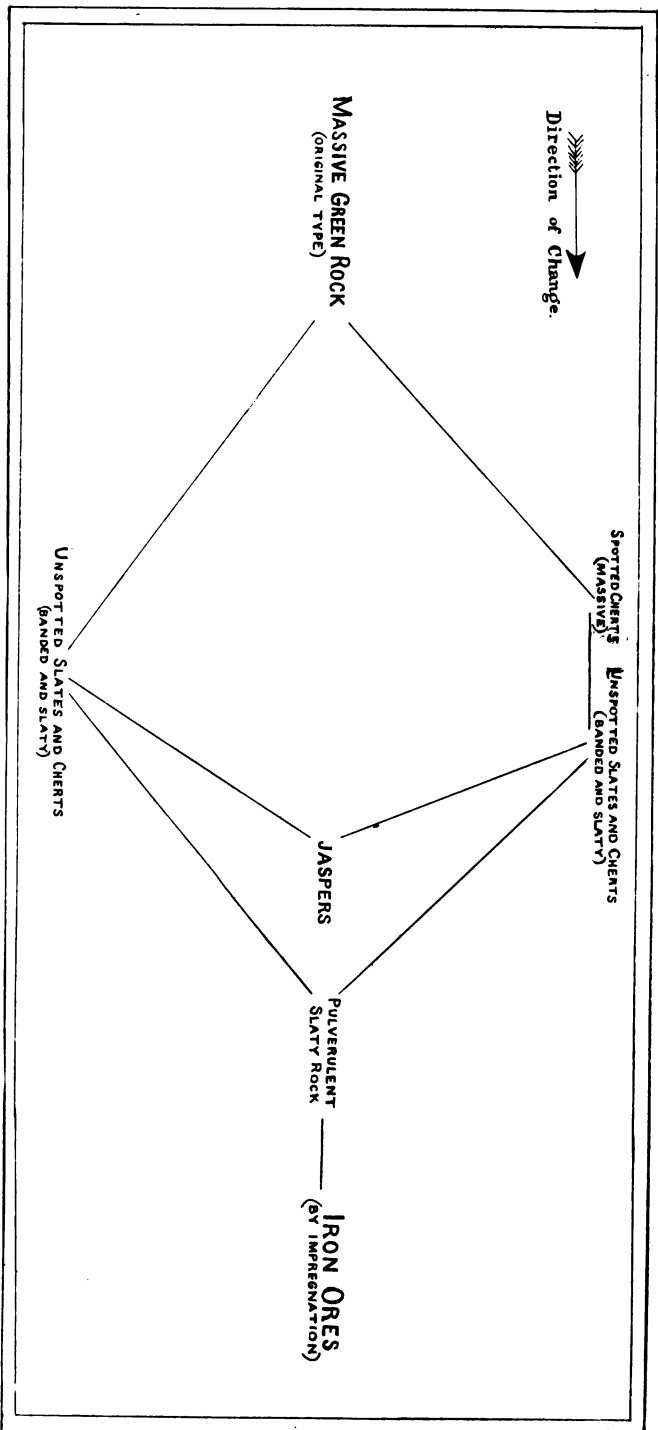
So far we have two main series, derived from a single initial type. The first series comprises the various stages of change under atmospheric influences, leading to the entire decomposition and the reduction to a clay-like rock. The second comprises the analogous processes of change as exhibited in a set of rocks which have lost the original massive and mottled structure, and have acquired a slaty or banded habit; these are derived either from the primitive type, or more often from some point in the first series. These processes lead finally to a clay-like rock which is identical with the rock resulting from the changes in the first series. In this first series the only apparent agency is one of weathering; in the second the change from the massive mottled to the slaty rock is not fully explained by the hand-specimen, but the subsequent changes which lead to the phases 25 and 12 are seen to represent weathering, as before.

The chief addition to these two divisions is the class of jasper-like rocks, represented in the scheme by 10 and 21. These are derived from certain very siliceous phases in each of the two main series: thus in the first series, they are seen to be derived from 2, and, in the second, from 14. Phase 21 is the end of this minor series. It is a crystalline "jasper," and is not known to pass into any other type. The process of development of this rock seems to be one of crystallization from the siliceous types whence it is immediately derived; and this process is sharply contrasted with the degenerative actions which operate in the formation of most of the members of the other series.

From this examination of the results of our tabulation and plotting, we may construct a simpler scheme of development, comprising only the grand divisions among the rocks. (Plate IV.)

ARRANGEMENT OF THE DIFFERENT GROUPS IN THE FIELD.

It is evident, from the fact that a single hand specimen often contains representatives of several widely differing phases, representing perhaps most of the larger groups, and that this occurs so frequently that a tabulation of the changes may be made from these specimens, that the different groups do not occupy any fixed horizon in the iron-bearing member. It is found in the field that any one of the groups may occur at any



DIAGRAM, SHOWING THE RELATIONS TO ONE ANOTHER OF THE PRINCIPAL CLASSES OF THE IRON-BEARING ROCK

point in the iron belt; and when this group gives place to another, the transition may take place vertically, so that one division overlies another, or laterally. In either case the boundary between the two is generally indistinct, and very irregular. Therefore it cannot be said that any one phase or division of phases is referable to any distinct horizon. The cherty and slaty rocks, however, seem to occur in large bodies chiefly in the upper horizons of the member; and the clayey and pulverulent slaty rocks are found at the surface, at any horizon, and lying above the less altered rocks which are akin to them. Indeed, it is ordinarily the case that, in a given vertical section where varied phases are encountered, those which are put near the end of the scheme, and so represent the effect of the greatest activity of decomposing atmospheric agencies, are found near the surface; and the fresher and firmer rocks, which are placed near the beginning of the diagram, at greater depths. These distinctions however, so far as we have seen, are incident to the alterations which have come about in the weathering and other changes in situ, and so probably have little stratigraphical importance, in that they do not necessarily represent divisions in the rock as originally formed.

CHAPTER IV.

MICROSCOPIC STUDY OF CERTAIN GROUPS OF THE ROCKS OF THE IRON-BEARING MEMBER.

In order to study more accurately the relation of the different phases to one another, and the processes which took place in the multitudinous changes there shown, together with the motive for these processes, thin sections were cut from the specimens described, embracing all the more important varieties. The study of these sections has confirmed the conclusions that were arrived at by a study of the hand specimens alone; and a clearer view of the gradual changes and their causes was also obtained. The evidence which proves the derivation of one type from another, and finally the ultimate derivation of all the types from a single uniform primary rock, will be treated independently of the evidence obtained from the hand specimens alone, as that evidence was deduced independently of it.

The method which has been adopted in tracing under the microscope the evolution of the rocks is somewhat different from that employed in the study of the hand specimens. In the macroscopic study the method was to classify all the types, occurring in specimens the locality of which was not brought into question, but representing the length and breadth of the iron-bearing region of the Western Mesabi; to show that they were referable to about thirty closely allied phases; to show that in the specimens certain phases were associated with certain others in a way that could be explained only by the derivation of one from another since the formation of the iron-bearing member; by classifying all these derivative phases in the different specimens, to show for a certain phase what phases were invariably below it in the process of change—i.e., were derived from it, either directly or indirectly—and what phases were invariably above it, i.e.,

gave rise to it, either directly or indirectly; and thus to work out the general scheme of evolution. In microscopic study the multiplication of the number of stages that may be observed, and the certainty and ease with which one may be traced into another, permit a more accurate and satisfactory variation of this method. Certain localities have first been selected from which many different phases have been collected, within a small area. Generally this area is represented by a single test-pit. These test-pits have a diameter only large enough to permit two men to work in the bottom; and they are usually sunk in the solid rock to a depth of less than ten feet. When different phases are found in the rock thus thrown out, they are confusedly intermingled, without definite order, one occurring as residuary cores or as decomposition borders to another. The phases that are thus found, occurring in this known proximity and relation to one another, are grouped for special comparative study. By this study it is invariably found that there is a definite scheme of development of one type from another, and this scheme and the causes which have led to the changes, are carefully noted. So varied are the phases, even within small areas like this, that in some of the groups the principal stages of nearly the whole process of change which characterizes the iron-bearing member are present. Sometimes the groups are taken from a still smaller space, a single specimen often furnishing opportunity to study a number of important changes. In some places again, where test-pits are set closely together, and the intimate connection of the rocks in them is obvious, specimens are selected from any of them to form the group for study. When these different chief groups have been studied, it is generally found that a certain type in one group is identical with a certain type in another, and thus two groups may be connected to extend the completeness of the general typical scheme of development. If in one group the type which stands near the head of the series as observed for this particular case is identified with a type which stands near the end of the series in another group, then the scope of the scheme is greatly extended; and if the groups turn out to be roughly parallel, the interpolation among the phases of the one of the phases which are closely related but not identical, belonging to the other, brings about an elaboration of the scheme. When the larger groups have been thus connected, the outlines of the main part of the general plan are found to be complete; and those phases which have been taken singly

from different localities may be found by comparative study to be identical with some of the phases in the scheme as already established, or to bear such evident relation to certain of these that their proper place is quite evident.

GROUP FROM SECTION 18, T. 58-19.

In accordance with this plan, the first group described is represented chiefly by sections 128, 129, 130 and 131. These are from the specimens of the same number, and are all from a single pit in the southeast corner of section 18, T. 58-19.

SPECIMEN 128.—Hand specimen shows a light greenish siliceous rock, grading into gray sideritic chert, dark chert, and bands of iron oxide. Three sections are cut from this, 128-A, 128 B and 128-C.

128-A.—In hand specimen a sideritic chert, dark gray, with cloudy white crystals of siderite scattered through it, or angular cavities left by the dissolution of these crystals. Fracture conchoidal.

Under the microscope, there is a ground-mass of very finely divided silica. This silica does not show the fibrous structure of true chalcedony, nor the clearly marked extinction and polarization colors of crystalline quartz. It consists of many very small grains closely packed together, which extinguish on revolution of the stage of the microscope; but without any marked polarization color other than a dull gray. The true nature of this variety of silica does not seem to be fully established, although it is the form which occurs frequently in many cherts and kindred rocks. Irving and Van Hise thus describe it in the cherts of the Penokee iron-bearing series:*

“It is that variety of silica or quartz which has in the polarized light a minute spotty appearance, due to exceedingly small individuals of quartz, mingled with more or less of silica, which is apparently amorphous. Hornstone, or flint, gives in thin section the same appearance, and the chert of the iron carbonates and hornstone have a very close macroscopic resemblance. That a portion of the silica is really amorphous, as indicated by the appearance of the section under the microscope, is further shown by its ready solubility in caustic alkalies.”

*Tenth Annual Report of the United States Geological Survey. The Penokee Iron-Bearing Series of Michigan and Wisconsin, p. 384.

In his work on the Novaculites of Arkansas, Mr. L. S. Griswold describes the silica of a rock which bears a very close resemblance to the one under consideration, as follows:*

"Under the microscope the ground-mass is seen to be composed of crypto-crystalline silica, extremely fine quartz grains, extinguishing in polarized light, but too small to give any polarization colors or other optical characters. The separate grains average less than .01 of a millimeter in diameter, there being from 6 to 10 grains in a linear distance of .05 mm. The extreme variation is about .01 to .001 mm. in diameter."

Rosenbusch treats this form of silica very briefly, as follows:†

"The so-called quartz of the siliceous slates and of related rocks requires more exact investigation, and probably does not belong to quartz, but to chalcedony."

This particular variety of silica is the most common in all the rocks of the iron-bearing member, as well as in the particular section under consideration. In a future brief consideration of its associations and characteristics as shown in its occurrences in these rocks, it will be found to resemble rather the less highly organized forms of silica, such as chalcedony and amorphous silica, than the truly crystalline quartz. In the descriptions of slides it may be conveniently referred to as crypto-crystalline silica, to distinguish it from the amorphous silica, the typical chalcedonic silica, having a fibrous arrangement, and the true quartz. All these forms occur in various proportions in different parts of the rocks described.

To return to our description of section 128-A, we find in the ground-mass of cryptocrystalline silica crystals of siderite, averaging about one-tenth of an inch in diameter. These crystals may have perfectly regular outline, either of single individuals or twins, or they may lack any portion of this outline. In the latter case the lines of growth terminate in such a manner as to show that the crystal was disrupted after its formation, and the space filled by the silica. These lines of growth are regularly placed, one within the other, and are rhombic, conforming to the outlines of the perfect crystals. They may be traced in some cases quite to the center of the crystal. The outer parts are freshest, and the siderite becomes clouded from decomposition, progressively towards the center, which is semi-opaque. These features show that the siderite is wholly of

*Annual Report of the Arkansas Geological Survey for 1890. Vol. III. Whetstones and the Novaculites of Arkansas, p. 123.

†Microscopical Physiography of the Rock-Making Minerals, by H. Rosenbusch. Translated by Joseph P. Iddings. Second Edition. P. 172.

concretionary crystalline growth, and the arrangement of the silica in its present form has gone on at the same time. This seems to be a continuation of the process described in its beginning under section 78. (See Plate VII, Fig. 1). The rock has been strained since the crystallization of the siderite, with the result that the crystals have been broken into small grains, which under crossed nicols extinguish at slightly different angles, according to the degree of straining. While this strain has thus wrenched the crystal, it cannot account for the many incomplete crystals, in which the portion broken off is wanting, and cannot be found anywhere in the rock. Often, after the crystal has had part of itself thus torn away, it has continued growing, the new lines of growth following the outline of the broken form, instead of the perfect crystal outline, as before. This shows that the crystals were not of their present size at the time of the breaking, but were only partly grown, and that since then the enlargement has proceeded.

SECTION 128-C. This slide contains three distinct bands of the hand specimen: 1, the sideritic chert; 2, a light green cherty band; and 3, a dark red iron-stained band which grades into nearly pure iron oxide.

In that part of 1 most remote from 2, the rock is exactly like 128-A. As it approaches 2, there is a distinct increasing tendency to a linear arrangement of the impurities of the chert, an increase in their amount, and a disappearance of the siderite crystals. What siderite remains becomes somewhat more decomposed. This transition rim is distinctly seen in the hand specimen, and grades into 2. The change between this band and 2 is marked, though there is a somewhat gentle gradation from one to the other. In 1, a siderite crystal has sometimes entirely disappeared, leaving a skeleton of hematite or limonite which fills one half or less of the cavity, the remainder being filled with cryptocrystalline silica. But perfect crystals occur on the very border of 1 and 2, lying partly in one and partly in the other.

2 represents in the hand-specimen a light-green, cherty band, from $\frac{1}{4}$ to $\frac{1}{2}$ inch thick. Consists of finely crystalline silica in interlocking grains of much larger dimensions and different characters than the silica of 1. This mass is colored green by a uniformly distributed, hardly individualized dust, which appears to be a decomposition product, and in which a carbonate may be recognized, in excessively small grains. There are no crystals of any kind. These greenish decomposi-

tion products are seen by a low power to be somewhat aggregated into little spherules. There is a distinct linear structure, and a certain differentiation into lighter and darker masses, around which the lines run.

3, in the hand specimen is more or less impregnated with iron oxide. In the slide it is seen to consist of hematite and limonite, with many small interstices occupied by grains of silica. The iron is densest on the line which marks the contact between 2 and 3.

Conclusion: 3 represents a line of mechanical weakness, along which iron-bearing waters have entered, impregnating this band, and to some extent replacing the silica.

SECTION 128-B. Contains varieties 2 and 3, substantially as described above, and variety 4.

4 is of the same color as 2, but is somewhat granular in texture. It constitutes a band about two inches wide, interrupted by a narrow ($\frac{1}{4}$ -inch) band of iron. It frequently contains very small rounded grains of a substance with a black color, vitreous luster and conchoidal fracture. In places the rock has become porous through weathering.

Under the microscope is seen the peculiar spotted structure which has already been mentioned in the study of the hand specimens of the different rocks. This structure is usually characteristic of the rock macroscopically, but in this case only microscopically. It is marked by the presence of a profusion of small rounded bodies, averaging perhaps one-tenth of an inch in diameter, thickly scattered through the ground mass.

These bodies may be of any color and have their outlines preserved with any degree of distinctness. Sometimes, when rounded, they suggest concretions and resemble the oolitic structure of limestones; and again when subangular, they suggest detrital grains. In still other cases they are sharply angular, and grade upwards in size to angular fragments of a diameter as great as two inches. In this latter case they are evidently fragments of a breccia. The nature and various causes of this structure will be discussed later. For these rounded bodies the term *granules* will be employed. This will cover not only those bodies which are of truly fragmental origin, whether original in the rock or secondary, but also others which resemble these closely, and make up perhaps 10 per cent of the whole number of granules. These latter will be

seen to be partly of concretionary growth, and partly the results of peculiar phases of impregnation of weak spots in the rock by iron oxide. The structure of which these bodies form the chief characteristic will be spoken of in general as a *spotted-granular* structure. When the granules are somewhat separated the siliceous filling between them will be referred to as the *ground mass*, but when, as often happens, they are closely packed together, the intervening matter will be spoken of as the *interstitial substance*, and as filling the *interstices*. The term *intergranular substance* will be used with the same signification.

In 128-B, variety 4, the granules are made up of particles of quartz, somewhat larger than those of 2, together with an evenly divided clayey and a green chloritic substance.* A large ragged fragment of the same nature remains at one side, and in this and the smaller granules there is a certain splitting and division going on. The change consists in a gradual rending apart of the mass, a slight darkening of the chloritic substance, and the filling of the interstices with crystalline or cryptocrystalline silica, varying from coarser to finer, but in general somewhat finer than that of the granules. Around the granules are often darker rims of the chloritic substance. The outlines of the granules are rarely rounded; they are usually angular, often not entirely separated from one another, and sometimes with the parting only begun. The interstitial silica may be xenogenous,† but it is probably derived from the silica already in the rock. This may take place in the following way: 1. The formation of silica by disintegration of the chloritic substance. This is accompanied by changes of volume which produce cracks. 2. Segregation of pure silica along these cracks, and the growth of these veins, splitting the rock. 3. A separation of iron oxide, attending the disintegration of the chloritic substance, producing the darkening of the residuary chloritic matter in the granules, especially around their edges.

Conclusion: Variety 4 is the original rock of the series exhibited in this specimen. In certain parts of the rock there

*The nature of this mineral is not here definitely stated, but as the description of sections goes on, it will be seen to have been of the highest importance in the history of the rock. Its exact nature and origin was not determined until after these descriptions were written, and as a knowledge of this is not essential to the understanding of the various changes, as it was not essential to their working out, the discussion will be reserved till later. In the descriptions it will be referred to as here, by the indefinite term "chloritic substance."

†In the use of this term and other convenient words of the same kind, the work of F. Posepny in his essay, entitled, "The Genesis of Ore Deposits," (Trans. Am. Inst. Min. Eng. Chicago meeting, 1898,) is followed.

has been a mechanical movement, doubtless resulting from the release of strains accumulated during the metasomatic changes. Along the cracks formed by this movement the rocks have been impregnated with xenogenous iron brought by percolating waters, and thus the bands of solid iron oxide were formed. In the rock immediately adjoining these actual cracks the slight schistose structure induced has given rise to selvage bands where the spotted-granular structure has been mainly replaced by a faint linear structure. Adjoining these bands the general straining of the rock, without any development of schistosity sufficient to permit the impregnation by iron, has operated to greatly accelerate the processes of metasomatism. This results in the almost total effacement of the spotted-granular structure, the simultaneous change of position of the silica and siderite, the concentration of the siderite, and the formation of the sideritic chert. Some of this siderite is to be found in the other forms of the rock; the rest represents the alteration product of the iron oxide under meagre access of oxidizing agencies.

SECTION 129. In the hand specimen greenish and flinty, standing about half-way between varieties 1 and 2 of section 128-A. It contains a residuary fragment one inch in diameter, which resembles variety 2 of 128-A.

Under the microscope there is a faintly-marked spotted-granular structure, much like that of variety 4 of 128-B. The granules are marked usually only by the chloritic substance, which is thinly sown, either in rims or in the center of the granule, or in little spherules; sometimes they are also marked by a finer grain of silica. The increase of silica, in proportion to the diminishing amount of the chloritic substance, forms the important distinction from variety 4, 128-B. Imperfect crystals of siderite are scattered through the rock: one of them, which is quite large, preserves one of its sides unbroken. This side passes through three of the granules and the intervening interstices, without any break, thus showing that the crystal was formed since the development of the spotted-granular structure.

Conclusion: This rock is derived from variety 4, 128-B, by the partial disintegration of the chloritic matter, the attendant separation of fresh silica, and the partial concentration of the siderite into crystals. A slight continuation of this process would give 128-A, and 128-C, variety 1.

An estimate of the proportion of the various constituents of this rock is: Silica, 90 per cent.; carbonates, 5 per cent.; chloritic and ferruginous matter, 5 per cent.

SECTION 130. The hand specimen is like 128-B, variety 4, but rather coarser in texture. Under the microscope it seems to be an intermediate stage between 128-B, variety 4, and 129. The granules are marked in the same way, but the chloritic substance shows a somewhat darker tinge, and they have been apparently traversed by fissures and redivided since the stage represented by 129. These fissures and interstices are filled by comparatively coarsely crystalline silica. In places the crystallization of the siderite seems to have just begun. There is some disseminated iron oxide. See Plate V, Fig. 2.

SECTION 131. The rock is nearly identical in outward appearance with specimen 14, described later, except that it contains reddish, crystalline patches that are nearly pure siderite. (These patches are what was classified as type 31 in the examination of the hand specimens, and will be seen to be merely a purer variation of the green rock). The rest of the rock is green, and granular in texture, with irregular fracture, and no sign of cleavage or schistosity. Under the microscope it is found to be made up chiefly of siderite. The red areas are comparatively pure, consisting of interlocking grains of considerable size. The green parts of the rock are made up of a ground-mass of smaller grains of siderite, in which is found a confused mass of minute brownish silicates with perhaps earthy hematite intermingled. Around the borders of these semi-opaque masses there are thickly interlocking radiating needles of actinolite. A very little silica occurs. This rock differs from 14 chiefly in the disappearance of the crystalline magnetite, and the great increase of the carbonate. There are seen in this slide two varieties of the granules. The first variety is identical with that of 14, except for the absence of the magnetite. The granules are marked by the presence of the semi-opaque brownish mass of silicates and actinolite, with a ground-mass of siderite and silica in small grains. The interstices are marked by more coarsely granular silica, and by larger crystals of actinolite, which radiate from the walls. The granules are hardly so distinct as those of 14, showing a change which may have resulted from the carbonatization of the magnetite. The second form of granules is best shown in the red, nearly pure siderite. Around the coarser grains here earthy iron oxide has formed, from oxidation of the siderite.

Sometimes this forms a network which surrounds each of the grains; sometimes it takes a broader circuit and forms an irregular ring, enclosing many grains, which are in every way similar to those without. Along this line whole grains of the carbonate have thus been changed to the oxide.

Conclusion: This rock occurs in the same pit with specimens 128, 129, and 130, which show a complete series of gradations in themselves. That 131 is connected with these in origin is evident. Either 131 is derived from the last stage (128-A) of the series, or the first stage (the fragment in 128-B, variety 4) is derived from it. The first supposition would involve the replacement of silica by siderite, which would be hardly probable, from a chemical standpoint, together with the effacement of the siderite crystals, and the introduction of an abundant chloritic and actinolitic ingredient. The second supposition is doubtless the correct one. It simply supposes the replacement of the carbonate of 131 by silica, and the reduction of the amount of the chloritic matter, which may be due either to silicification or to leaching. In other specimens the actual process is seen by which a rock like 128-A may be derived from a rock like 131. The change consists in the infiltration of silica, which took place early, the contemporaneous replacement of the larger part of the siderite by the silica, and the segregation of the remaining siderite into crystal form. It is also possible that the larger amount of silica in 14 may be due to some slight original difference in the two rocks.

FIRST GROUP FROM SEC. 33, T. 58 17.

The specimens constituting this group are all from the same pit,—27, 28, 29, 157, 158, 159, 160 and 161. The slides are cut from 27, 29, 160 and 161. In this group the derivation of one phase from another is sufficiently distinct in the hand-specimen, by the same evidence as has been already described, and which will not be repeated here.

SECTION 27-A. This is a rock containing four distinct phases. In the hand-specimen the boundary between neighboring phases is quite distinct.

Variety 1. Under the microscope this is seen to be the original rock, so far as this specimen goes. It is made up of silica, siderite, magnetite and hematite. The magnetite occurs in small irregular masses, never with crystal form. It generally forms a residual core in the middle of a mass of siderite, or, more rarely, of hematite. In the latter case both magnetite and hematite are sometimes imbedded in a mass of the carbon-

ate, so that it seems that the change to a carbonate took place at one time, and that at a later time the changing conditions favored oxidation to a hematite. In the larger siderite masses there is generally a kernel of magnetite in the middle, and in addition, grains scattered irregularly. There is never any magnetite at the periphery of the siderite.

Hematite, red and earthy, occurs only as a decomposition product, almost always of magnetite. It forms irregular masses or streaks. In this way it surrounds the magnetite from which it is derived, and has also made its way into cracks in the silica. Siderite appears to be in all cases a decomposition product of magnetite. The larger masses, which almost always contain the residuary kernels of magnetite, have irregular shapes. As they grow smaller the decomposition has been more complete, and the kernels of magnetite are smaller and fewer. The smallest ones do not have these kernels at all, and these have often obtained a perfect rhombic form. These crystals, however, form but a small part of the whole mass of siderite. Rarely, a perfect crystal of siderite may be found in the midst of a mass of decomposing magnetite.

There are still indications of the existence of the granules so common in other sections. Frequently a narrow rim of magnetite or hematite, or both, gives the familiar outline of one of these forms. The interior is generally filled with silica like the ground-mass. From a study of other sections, it seems probable that the history of these forms is as follows: A granule made up mainly of siderite was oxidized along the edges into hematite. At this stage the remaining siderite was replaced by silica. Subsequently the hematite was changed into magnetite.

The ground-mass is composed of cryptocrystalline silica, clouded with some slight amount of clayey matter.

An analysis of this rock was made by C. F. Sidener, with the following results:

ANALYSIS OF SPECIMEN 27-A, VARIETY 1.

Silica.....	SiO	86.35	per cent.
Alumina.....	Al ₂ O ₃	.78	"
Sesquioxide of iron.....	Fe ₂ O ₃	7.41	"
Protoxide of iron.....	FeO	3.46	"
Lime.....	CaO	.01	"
Magnesia.....	MgO	.05	"
Potash.....	K ₂ O	.01	"
Soda.....	Na ₂ O	.12	"
Water.....	H ₂ O	.01	"
Carbon dioxide.....	CO ₂	1.22	"
Total.....		99.42	

Variety 2. The granules which are largely filled by hematite or magnetite become more plentiful at one side of the space occupied by variety 1, and finally form a distinct band. This is variety 2. In the hand specimen it is strongly marked, and has the appearance of red jasper. Under the microscope the difference of structure is seen to be trifling. Most of the siderite of variety 1 disappears, and is oxidized to red hematite, which penetrates and stains and probably to some extent replaces the silica of the granules. All stages of the process may be seen in different parts of the band, which is about $\frac{1}{4}$ inch thick. The magnetite also decreases in quantity, but less rapidly than the siderite.

Variety 3 is characterized in the hand specimen by its black color and flinty fracture. It constitutes a band of about the same width as that of variety 2, of which it contains fragments. Under the microscope it is characterized by a fine irregular striping, parallel to the banding of the hand specimen. The ground-mass is of very fine cryptocrystalline silica, and is clouded with grains of sub-microscopic size, apparently of iron oxide and greenish decomposition products. It is sprinkled with small crystals and irregular grains of siderite, grains of magnetite, and blotches of hematite. These bodies have been frequently drawn out in a line parallel to the striping, and the lines of this structure are marked by the accumulation of iron oxide along them. While the transition from variety 1 to variety 2 is gradual, and is marked by a chemical, but no structural change, that from 2 to 3 is rather sudden, and follows a more or less well-defined line. The lines of striping of 3 sometimes run around large fragments of 2, and again they cut directly across, even breaking through the red granules. This indicates a mechanical shearing.

Variety 4 appears as a greenish slate in the hand specimen, with somewhat well-developed cleavage. Under the microscope, the line between it and 3 is well defined. It is straight in its general course, but exceedingly irregular in its details. There occur in 4 rhombic crystals which seem to be of decomposed siderite. When these project beyond the line into variety 3, they have often had one end broken off and carried a little way, in a direction parallel to the schistosity and the elongation of the particles of 3. A confused mass of decomposition products forms the main body of variety 4, and gives it its green color. These seem to be chiefly made up of the iron oxides, epidote (?), calcite, and chlorite, with the latter

predominating. The schistosity is well marked by thickening of these materials along the lines of parting. A fragment remains which still has the structural features of variety 1.

Conclusion: Varieties 2, 3 and 4, were formed from variety 1, simultaneously, following a local schistosity, which was probably induced by a slipping or fault in the rock. The smooth outer surface of variety 4 in the hand-specimen may be the line of fracture. The schistosity realized its maximum effect in variety 4, and produced a chloritic slate; in variety 3 the lines of cleavage are microscopic, but the motion served to destroy the structural features of 1; in variety 2 there was no rearrangement of structural features, but this band was affected by the oxidizing agencies which penetrated through 2 and 3, and the oxidation of siderite and magnetite to hematite followed, producing the red color of the rock.

SECTION 27-B.—This is the same as 27-A, type 1. Some fine examples of the decomposition of magnetite to siderite may be noted.

SECTION 29.—Hand-specimen banded, with slaty cleavage; in parts heavily iron-bearing. That this is derived from 27 is shown in the changes noted in the specimens at the pit. Under the microscope, a very perfect schistose structure. It resembles 27-A, variety 4, with which it is really very closely related. The chief constituents are magnetite, hematite, silica and chlorite. The darker bands are made up almost entirely of magnetite and hematite (proportion about, magnetite 60 per cent., hematite 40 per cent.); the light green bands mainly of chlorite and silica, and between the two there are transition stages. There is also some calcite, some epidote and a very little pyrite. None of the principal minerals have crystal form, but are in irregular bodies, roughly elongated and parallel. The association of the chlorite suggests its formation from the magnetite or hematite by uniting with the silica, for the chlorite is in places in borders along the edge of the magnetite, or lines the interstices. The silica is finely crystalline. This change in the nature of the silica may be due to an infiltration from without, but more probably to a recrystallization of the cryptocrystalline silica. Many instances of this latter change have been noted.

SECTION 160-A. Hand specimen shows a perfect slaty cleavage; is banded with light green and dark red. The bands appear to differ in color rather than in texture; they have been brecciated and faulted, the fragments being sometimes as much

as two inches in their greatest length, and oriented in all positions to the banding. Under the microscope, the light bands are composed of a mass of finely-divided chlorite and iron oxides, small grains and crystals of magnetite and hematite, with calcite and some siderite. These lighter bands are almost identical with variety 4, 27-A; and the darker ones find their counterpart in 29. A set of roughly parallel fine partings, marked chiefly by iron oxide, run through the mass. The darker bands, which have been deeply impregnated with iron oxide, probably represent a plane of greater shearing than the light ones. Subsequent to this shearing and the ensuing changes there has been another pressure, resulting, in certain zones, in the brecciation and intermingling of the bands. This is well shown on one side of the section. Angular fragments of all sizes, still retaining their original structure and schistose lines, are confusedly intermingled. In some of these displaced blocks the lines of schistosity run at right angles to the general schistosity of the rock. The planes of greatest brecciation seem to lie parallel to that of the banding.

SECTION 160-B is cut from the same specimen. It has the same characters, but is somewhat more brecciated, and contains a normal fault of about one-half inch throw (vertical). There is a marked fault-breccia developed, and a twisting of the layers on either side of the fault, indicating the direction of movement. The course of the fault is irregular.

SECTION 161-A. Compare 27-A, variety 2. The hand-specimen shows a dark-red rock, somewhat mottled with very fine darker spots, and faintly banded. Fracture conchoidal; no cleavage. This weathers on both sides to a light gray rock, more porous and friable, with granular texture, and a faint cleavage. 161-A is cut from the red rock. It resembles 27-A, but is somewhat more stretched, producing elongated forms of the granules. These granules are closely pressed together. They are made up mainly of silica, stained with a sufficient quantity of iron oxide to render them opaque. When the silica is not thus stained, it is seen to be variable from cryptocrystalline to finely phenocrystalline. Siderite is present, occasionally in small crystals, usually in broken and irregular fragments, which may be separate from the granules or may be associated with them. The evident derivation of this rock from 27-A, variety 1, explains this. In parts of the section there is a distinct wavy linear or fibrous structure. In these parts the granules are often cracked, often broken

apart, sometimes shred and mingled indiscriminately. The interstices of silica have also been led by the stretching process to assume elongated and rounded outlines. The silica consists almost invariably of a nearly amorphous mass, which shows under the highest power, with crossed nicols, only a few scattering grains where extinction can be detected, the rest remaining uniformly dark. These scattering grains are cryptocrystalline. A comparison of this silica with that of 27-A, variety 1, shows by how small changes the fine cryptocrystalline silica reaches such a state of minute division that the individual grains cannot be detected under the highest magnifying power, and so must be classed as amorphous. It seems eminently probable, however, that this silica is really individualized, in grains of sub-microscopic size, and that its true nature is as far from colloid silica as it is from quartz.

SECTION 161-B, is cut from the weathered gray rock. The shearing seems to have been little greater than in 161-A, but the change is chiefly one of disintegration. In parts the fibrous structure is seen, but generally it is not distinct. The spotted-granular structure has become faint, and were it not for the association of this rock with 160-A, could not be identified with certainty. The disseminated iron oxide is collected in irregular bunches, or is scattered as dust-like limonite, in which form it stains slightly the whole section. The larger bunches of this iron have been dissolved out, leaving pores that riddle the rock, and attendant upon these changes has been the infiltration of calcite, which forms clusters of small grains. The silica is mainly apparently amorphous, as in 160-A.

SECOND GROUP FROM SECTION 33, T. 58-17.

The two specimens of this group, 164 and 166, are from the same pit, which is situated about half a mile southwest of the pit whence the group just described was taken.

SECTION 164. In hand specimen, a jasper, consisting mainly of dark gray silica, faintly marked with somewhat brecciated bands of red and light gray. Conformable with the banding there are thin seams of crystalline quartz, and also a vein of the same material which is about $\frac{1}{4}$ inch wide. A prismatic jointing is present. Compare with the "jasper" from Iron Cliff, (spec. 40, see p. 61.) Under the microscope the silica is seen to be mainly truly chalcedonic, with radiating fibrous structure. On the one hand, this grades into a variety where the individuals are so small as to be hardly or not at all discernible,

and so may be called amorphous, and on the other into fine grains of quartz. The traces of the spotted-granular structure are distinctly discernible in this rock: (1), by the presence of clustering patches of iron oxide, which appears to be mainly crystalline hematite, and occasional associated sheaves of actinolite; (2), by the difference of the silica of the granules from that of the interstices. Interstices may be found which are marked by crystalline quartz grains, around the edges of which come the coarser chalcedonic, then the finely chalcedonic to amorphous silica, and finally the iron oxides. Conclusion: This rock has been altered by metasomatism rather than by dynamo-metamorphism. The spotted-granular structure has not been sheared out of existence, but has been nearly effaced by changes of a chemical nature.

SECTION 166. In the hand specimen there are two parts. One is a red, mottled band about $1\frac{1}{4}$ inches thick. The color is given by thickly crowded red granules which occur with small bunches of magnetite, in a dark gray ground-mass. This band is somewhat brecciated, containing angular fragments of darker rock (which are stained red around the edges), as much as half an inch in their greatest length. The rock seems identical with 27-A, variety 2. The darker material forms the rest of the specimen, and from it the slide is cut. From this the red part has been formed by a weakening under stress, slight brecciation, and subsequent oxidation. Under the microscope, it has the spotted-granular structure, considerably altered, though not nearly so much so as in 164, which is derived from it. Resembles 27-A, variety 1, but differs from it in the disappearance of nearly all of the siderite. In 27-A, this is an important constituent, but here it occurs only as scattered films. The granules are strongly marked, and are made up of magnetite, with some earthy hematite and cryptocrystalline silica. Sometimes the granule is chiefly of hematite, but usually it is of clouded silica, with magnetite cores, rims, or straggling internal skeletons. The silica of the interstices is usually finely phenocrystalline, and at the contact between this and the cryptocrystalline silica of the granules there is a curious ragged band, which suggests that the finer is passing into the coarser by crystallization. This is supported by the fact that the coarser variety is also found in crevices in the middle of the granule, which are without apparent communication with the interstices. The comparison with 27-A, variety 1, suggests the same thing.

Summary: We may believe that 27-A, variety 1, and 166 were probably originally almost identical. Waters dissolved part of the iron of 166 and deposited it further on in the rock as carbonate, giving rise to 27-A, variety 1, (27-B). The loss of volume caused a contraction of 166, which resulted in the development of the prismatic jointing; and of the horizontal parting, which is marked by the white quartz seams of 164. Then the processes of metasomatism—the governing motive being the striving towards greatest stability—went on, and, with the aid of crystallization, brought about the rock at Iron Cliff (section 40, see p. 61), where the silica is all crystalline quartz, and the spotted-granular structure has entirely disappeared. The carbonate deposited in 27-A, variety 1, together with the carbonatization of some of the original oxide of the rock, caused an expansion which resulted in certain movements and the production of certain zones of slight shearing. The result was: (1), the intimate mingling of the materials which had been so long segregating under metasomatic forces, and so in some wise a regenerative effect; and (2) the exposure of these materials to xenogenous infiltrated matter. This led to the formation of minerals which somewhat resemble the original ones, such as chlorite. From the comparative study of all the specimens it will be seen that a green chloritic mineral was very important in the least altered forms of the rock, and seems to have been there as early as we have any record. But in these sheared rocks the chlorite is disseminated irregularly in minute particles, while in the least altered rocks it is in firm, distinct masses; the iron is in a finely divided condition, instead of being crystalline; and a fine slaty cleavage replaces the massive structure. In an intermediate rock, originally identical with 166 and 27-A, variety 1, but lying between them, the result would be a complete carbonatization of the iron; the attendant removal of most of it so gradually as to prevent the accumulation of strains; and the concentration of the rest, to produce a sideritic chert like 128. Specimen 27-A, variety 1, would also, by a continuation of the already far advanced process, become a typical sideritic chert like 128, if it met with no further mechanical accidents.

THE IRON CLIFF GROUP.

The two specimens of this group, 40 and 41, are from the same pit in the hill known as Iron Cliff, in sec. 36, T. 59-17. As a whole, this hill is a peculiar phase in the iron-bearing

rocks, for it is in large part made up of banded crystalline iron, often magnetic, and crystalline silica, or "jasper." There are few of the friable phases and sudden alterations that are seen in other parts of the field. The rocks much resemble the typical banded "jasper and ore" of the Vermilion range. They are marked by a prismatic jointing.

SECTION 40. In the hand specimen there are rather pronounced bands of "red jasper," "black jasper," and nearly black crystalline hematite, with magnetite. That this banding is secondary and has no relation to the original structure (indicating neither planes of detrital or chemical deposition, nor of the flow of an igneous mass), is shown by the course of the bands, which, instead of remaining parallel, often unite, and again fork and run at different angles. Besides the banding there is a fine lamination of differently colored silica. Both macroscopically and microscopically the rock shows a close resemblance to 35 (described later, see p. 64), from which phase it is derived by a very slight change.

Under the microscope it is seen to consist of silica, magnetite and hematite in about the following proportion: Silica, 90 per cent.; magnetite, 8 per cent.; hematite, 2 per cent. The silica is in the form of crystalline quartz, in small grains of somewhat uniform size, with irregular outlines. The magnetite is in clustering masses, with distinct though somewhat rounded crystal outlines, which are about the same size as the grains of quartz. In some parts of the silica bands they are somewhat more thickly strewn than in others, constituting under the microscope irregular and indistinct bands, and in the hand specimen a fine lamination of light and dark silica. This dark silica, when occurring in a broad band, constitutes the "black jasper." In bands the magnetite has been somewhat oxidized to hematite, mainly in the form of martite, thus forming the "red jasper" of the hand specimen. In another band the magnetite has collected into a dense mass. This is about $\frac{1}{8}$ inch wide. It is densest in the middle, but even here there occur interstices filled with quartz. Toward the periphery it becomes more scattered, thin bands of it alternating with layers of silica, till it grades off into the black jasper. Along this outer margin there is considerable decomposition to hematite. There is in this rock no trace of the spotted-granular structure. The silica grains are of about the same size as the predominating larger ones of section 35. (See p. 64.) This shows the change from the smaller cryptocrystalline variety

to the coarser—an operation contemporaneous with the comminution, distribution, concentration, and recrystallization into bands of the iron, and the obliteration of the spotted-granular structure.

SPECIMEN 41. Color, dark red. The granules of the spotted-granular structure are distinctly visible to the naked eye. There are scattered through the mass large grains of crystalline quartz, which have the shape, size and appearance of sand-grains. These are not arranged in any definite layers, except that they become more abundant in the part of the specimen represented by 41-B. This part grades directly into 41-A, described above. It is darker, and in place of the spotted-granular structure has developed a slight cleavage. This may be due to shearing and subsequent decomposition, or to decomposition alone. 41-A has a conchoidal fracture, and neither jointing nor cleavage.

SECTION 41-A. In the slide there are two varieties, differing from one another slightly and grading together. *Variety 1*, in the centre of the slide, has the normal spotted-granular structure. The granules are rounded or sub-angular, are closely packed, and are made up of silica, hematite and chloritic and clayey matter, in the order of abundance named. The silica is finely cryptocrystalline and is clouded with iron oxide. Magnetite occurs in irregular fragments, either intimately mixed with the hematite or as cores in the hematite masses. There is a slight tendency for the granules to lie with their longer axes roughly parallel. This is due to a stretching under mechanical pressure, as will be shown further on. The most striking feature in the rock is the presence of the large angular grains of crystalline quartz, which were mentioned in the description of the hand-specimen. This quartz is entirely different from the rest of the silica in this slide, and from the usual silica of any other of the slides of the iron-bearing member examined. They appear to be sand-grains. They are perhaps fifty times as large as the largest grains of the other silica; they are traversed by cracks which indicate great straining which the rest of the rock appears not to have shared; and there is a variety of shading in them, due to the relative abundance of foreign inclusions. The silica in which they are embedded varies from cryptocrystalline to chalcedonic, the latter showing radial fibrous structure. These grains must be considered fragmental. *Variety 1* is surrounded by and grades into *variety 2*.

Variety 2 is marked by a distinct parallel schistose structure, the lines of which curve around the fragment of variety 1. Here the granules are pulled out into long masses parallel to the lines of the schistose structure, or assume torn and irregular outlines in place of the rounded ones. The coarser and the finer intergranular chalcedonic silica are confusedly intermingled, or drawn out in the same way as the granules. There is here a decided predominance of the chloritic ingredients over the iron oxides, while in variety 1 the reverse is decidedly true. The grains of apparently fragmental quartz have also undergone the same force as the other ingredients. They have sometimes been broken, and the pieces separated from one another by small distances, in the direction of the lines of the schistose structure.

Conclusion: This rock has undergone a slight mechanical shearing, as is shown by the torn and irregular outlines of the granules, and their stretching in a common direction, by the breaking and separation of the fragmental quartz, and the development of chloritic and clayey matter in place of the iron oxides. This motion must explain the motive for segregation in bands of the materials of section 40. It is probable that these bands follow planes of slight weakness, which originated at the same time as the shearing in 41.

SECTION 41-B. From the lamination of the hand specimen, this seems to be a more complete shear-zone. Under the microscope, the rock is seen to have altered to a black, opaque mass, which by incident light is seen to consist mainly of the iron oxides. The traces of granules are very faintly shown. This mass is liberally sprinkled with the fragmental quartz grains. They have undergone no change, save for a slight corrosion of their margins. There is a single residuary area of chalcedonic silica. The change in this rock has probably been due to the straining, which produced a comminution of the fragments of the rock; followed by the action of percolating waters, which dissolved the cryptocrystalline and chalcedonic silica, and replaced it by iron. The fact that the quartz grains were not attacked is another proof of their independent origin. This specimen is only about twenty feet from the quartzite below it, on which the iron bearing member is here seen to rest. These fragmental quartz grains are of the same nature as those of the quartzite.

GROUP FROM THE CHICAGO PROPERTY,
SEC. 4, T. 58-16.

The sections in this group are from specimens taken from adjoining pits on the Chicago property. The pits farthest from each other are about 150 yards apart. In general the material at the different pits is very much alike, but certain phases differ from others in the same pit. The sections are from specimens 35, 36, 37, 39, and 53.

SECTION 35. In the hand specimen, it seems to consist mainly of silica, stained light red and having a jaspery appearance, and magnetite. While these two ingredients are irregularly distributed, yet there is a tendency to a concentration into indistinct, non-persistent, roughly parallel bands. In the darker bands magnetite prevails, in the lighter ones the silica. Along the darker bands pitted decomposition has set in. Under the microscope the granules and interstices of the spotted-granular structure are often distinctly seen, but are often faint, and sometimes nearly obliterated. The magnetite is in irregular masses, often showing a clustering motive, with distinct outlines, yet with no strict crystal boundaries. In one place it is clustered into an irregular darker band without definite boundaries. This band, save for the slightly increased proportion of magnetite, is identical with the rest. As is usual, the rock on one side of the band is much poorer in iron than that on the other, showing that most of the iron was derived from one direction, and pointing to waters acting under the influence of gravity as the chief cause. The silica varies from cryptocrystalline to finely phenocrystalline, the latter somewhat predominating. The two are sometimes mingled confusedly; but where the spotted-granular structure is best preserved the granules usually consist of the finer silica, and are surrounded by the coarser grains of the interstices. The position of the magnetite in the section has no relation to the traces of the granules; hence the silica, even in this finely divided form, is stabler. Scattered crystals of siderite occur, generally more or less oxidized.

SECTION 36. From the same pit as 35. In the hand-specimen is light-gray and siliceous, with small grains of magnetite visible to the naked eye. There is no banding, but the rock is riddled with pits, which are lined with a crumbling powder that appears to be partly limonitic. Under the microscope, the estimated proportion of different constituents is: Silica, 92 per

cent., Magnetite, 4 per cent., Limonite, 2 per cent., Siderite, 2 per cent. The powder of this rock gave reluctant effervescence with cold dilute hydrochloric acid, but effervesced freely on warming. In general structure the rock is like 35. The outlines of the granules can everywhere be distinctly traced, though in most cases they are marked only by a slight difference in the size of the silica grains, and by a cloudy yellowish color. The magnetite bodies have the same general habit as in 35, but are fewer, and have occasionally distinct crystal boundaries. Micaceous hematite occurs in small blood-red specks, associated with the magnetite. Siderite appears scattered through the section in very small, vaguely outlined forms. It often surrounds magnetite, in which case the magnetite loses its crystal outline. When present in any considerable body it is usually rusty with oxide. It thus appears to be entirely of secondary origin. Two or three of the "pits" described in the hand-specimen are shown in the section. The original distinction between them and the smaller decomposition spots which can be seen only under the microscope seems to have been a clustering of magnetite. At present they are characterized by this, by a lack of regular outline and by the decomposed condition of the adjoining rock. In this decomposition border siderite is found in numerous small irregular clustering grains, which surround the magnetite, when the latter is present. Conclusions: In the process of change magnetite has become segregated into certain spots more thickly than in others. On the freer access of oxidizing agencies, the decomposition has begun at first around these groups, since the iron is more easily attacked than the silica. The change of the iron is first of all to a carbonate, after which it is taken into solution and carried away, to be deposited further on, leaving an empty pit, lined with products not yet far enough advanced in decay to be taken into solution. The extension of these rust-spots in time decomposed the whole rock. The hand-specimen in places is already more than half decomposed. (See Plate IX, Fig. 1).

SECTION 37-A. From a pit about eighty yards from the first. Resembles 36, both in the hand-specimen and under the microscope. The chief difference is the presence of calcite in spots, these spots corresponding, in size and distribution, to the rust-pits of 36. The granules can be distinctly observed everywhere, chiefly by the difference in grain and coloring of the silica, as explained for 36. The magnetite has lost all con-

nection in position with the granules, is sometimes with crystal outline, and has a tendency to congregate in clusters. These spots are also characterized by the presence of siderite and calcite (or magnesite) in larger quantities than in the rest of the section. The calcite is usually in large, clear grains, showing cleavage; the siderite is in small irregular patches, as in 36. The history of this structure is as follows:—1. The concentration of the magnetite into clusters. 2. The beginning of oxidation at these points, (into siderite or hematite). 3. The infiltration of calcite from extraneous sources into the spaces opened by decomposition. 4. The action of the calcite on the undecomposed magnetite to produce siderite. 5. In the next stage the solution of these carbonates would give the peculiar rust-pits of 36. There is a very small amount of actinolite in the rock.

SECTION 37-B.—From the same specimen as 37-A, into which it grades on some sides, and from which it is separated on others, by a rather distinct mechanical crack. It is apparently a residuary fragment, although on the side where the crack intervenes between it and 37-A it has the semblance of a pebble. It is fine-grained, and green in color. There are in 37-A much larger quantities of calcite than in 37-B, and the crack between the two seem to have been the passage-way for the waters that brought the mineral. A fine vein of calcite (magnesite?) traverses 37-B. The crack that has been thus filled is much wider than that between 37-A and 37-B. The result was that the waters found sufficient passage-way, and instead of forcing their way into the rock and impregnating it with calcite, as in 37-A, they carried off some of the country rock in solution, in the near vicinity of the walls of the fissure, and brought about a general decomposition; thus giving rise to a distinct broad dark selvage strip on both sides of the vein. Across this strip and the vein the section was cut.

Under the microscope, the vein, which is at its broadest point about 1-16 inch in diameter, is seen to be mainly filled with well-crystallized calcite, showing cleavage, and often the successive stages of growth, in perfect crystals. Iron in the form of earthy hematite and siderite is scattered between the crystals and along the walls, in such manner as to show that it is secondary to the original material of the vein. In the selvage strip of the country-rock the traces of the spotted-granular structure are almost entirely obliterated, being only faintly shown in places under crossed nicols. The predominating feature is the ground-mass of very finely cryptocrystalline

silica, more uniform and finer than that of 37-A. Iron is almost lacking, save for its occurrence in earthy, semi-opaque masses of decomposition-products. In these masses actinolite, chlorite, calcite, and siderite, probably occur. The change of the silica under freely oxidizing forces is very important. When these agencies do not have access, the reverse or crystallizing process takes place, as is seen in 40 and many other sections.

SECTION 39. From same pit as 37, and closely associated with it. Is distinct in appearance from 37, owing to the mottling which the distinctly marked granules produce. In color light-green; fracture conchoidal; no cleavage or jointing. Under the microscope the rock is seen to be much less altered than 37. The primary granules which correspond to the granules of 53-1 make up about 60 per cent. of the entire mass. Surrounding these is a secondary border which makes about 25 per cent. of the mass. This leaves only about 15 per cent. of the interstitial pure silica. The general structure resembles very much 14 and 17, which will be described later. The primary granules are composed of a compact green chloritic substance, in firm masses traversed by roughly parallel partings; it is slightly pleochroic. Others are darker and opaque from decomposition products, such as earthy iron oxide. Some of them have internal magnetite fragments. Sometimes carbonate, either fragmental or crystalline, but generally much decomposed, is found. These granules rarely have well-rounded outlines; they are usually ragged and angular. Small fragments are scattered everywhere. Surrounding these granules as a decomposition rim is a body of pale-green, finely matted actinolite, in clusters and sheaf-like forms, with which are intimately mingled limonite, cryptocrystalline silica, and carbonates. Last of all, the small angular interstitial cavities are filled with grains of finely phenocrystalline quartz.

SPECIMEN 53 is from a pit which is about 100 yards southwest of the last. This pit passed through ten or twelve feet of soft black slates, and then through two or three feet of the hard gray siliceous rock belonging to the iron-bearing member, substantially as described for the other specimens in this group. The contact between the slates and the iron-bearing rock is well-marked, and there is no sign of transition between the two. The slates in nowise resemble the iron-bearing rock. They dip gently to the south. South of this pit all explorations have revealed the presence of the upper

slate member. Specimen 53 is taken from the contact of the two formations. Section 53-1 is cut from that part of it which belongs to the iron-bearing member, and 53-2 from the soft black shale.

SECTION 53-I. The hand-specimen is a dark greenish-gray; fracture in general irregular, but has a tendency to a rough horizontal parting and also to a vertical jointing; structure, spotted-granular; contains a rounded fragment resembling a pebble, which may be a pebble or a residuary fragment.

Under the microscope the ground-mass is a finely phenocrystalline silica, the grains of which interlock in such a manner as to put their formation in place beyond a doubt. Through this are scattered rounded, angular or broken fragments, the largest of which perhaps average 1-16 inch in diameter. Prominent among these are rounded grains of crystalline carbonate (probably calcite or magnesite), which from their appearance were almost certainly originally detrital. The cleavage is very well shown, and they are tinged a dirty brown by impurities which have found their way into the cleavage crevices. Their appearance is strangely contrasted with the calcite (magnesite?) which has entered since the formation of the rock. This is very abundant, occurring as an aggregate of very small grains, in color pure white. In this manner it forms borders around the granules, or small bunches in the interstitial silica. It never shows cleavage or crystal form. (See Plate V, Fig. 1; also Plate VIII, Fig. 1).

Besides the carbonate, there are rounded, angular, irregular, or shattered masses of the green chloritic substance, which also in many cases may be detrital, though often they have been disrupted by the movements in the rocks subsequent to consolidation.

In the majority of the greenish bodies, however, the green mineral has been decomposed, depositing silica in very small cryptocrystalline grains, as a result.

In the majority of the granules it is evident that the silicification has gone on in place, for it has been to some extent accompanied by slight movements, which seem to have produced the torn and irregular forms.

Conclusion: In this section, fragmental and non-fragmental material is mingled. This is the extreme upper contact of the iron bearing member. Compare, on the extreme lower contact, sections 41-A and 41 B. (See pages 62, 63.) The rock has evidently already gone through a great deal of metasomatic change, as is

evidenced by the interstitial secondary silica, the secondary silica of the greenish granules and the borders of secondary carbonate. In this case it seems clear that replacement has had nothing to do with the development of engranular silica, for the granules of carbonate have not been attacked, but remain quite unaltered. The conclusion is inevitable that the green material is extremely unstable under circumstances where the carbonate is not affected.

SECTION 53-2.—In hand-specimen black and soft, with perfect slaty cleavage. The line of contact with 53-1 is even and distinct. Under the microscope, about 60 per cent. of the mass is seen to be made up of a carbonate which resembles calcite. It does not effervesce with cold dilute hydrochloric acid, however, but only on warming, and analysis shows it to be entirely magnesite. The rest of the section is occupied by fine clouded greenish material. The structure of 53-2 has not the slightest resemblance to that of 53-1, no more than has the mineral composition. The structure of 53-2 is the familiar one characteristic of a fragmental rock, and especially of a limestone. The grains of magnesite are scattered uniformly through the section; intermingled with them are irregular and ill-defined flakes of the greenish materials, which are apparently of later origin than the magnesite. The rock bears no resemblance to any of the specimens from the iron-bearing member that have been examined, not even the sheared and sometimes calcified cherts and slates, for these have a linear or fibrous structure indicative of their origin; 53-2 has no trace of this, nor yet any of the spotted-granular structure; nor does it show any tendency to concentration and crystallization. Taken into account with its field relations as described, and its resemblance to rocks like 76 and 112, which will be described later, we must consider it as the bottommost layer of the slaty series which immediately overlies the iron-bearing member, and that the line of demarkation between 53-1 and 53-2 is the line of contact between these two grand members of the Animikie series.

An analysis of this rock gave the following results:

ANALYSIS OF 53-1 (CHEMICAL SERIES NO. 236).

BY C. F. SIDENER.

		Per Cent.
Silica.....	SiO ₂	41.73
Alumina.....	Al ₂ O ₃	4.07
Sesquioxide of Iron.....	Fe ₂ O ₃	14.43
Protoxide of Iron.....	FeO	19.85
Lime.....	CaO	.02
Magnesia.....	MgO	4.41
Potash.....	K ₂ O	.02
Soda.....	Na ₂ O	.18
Carbon Dioxide.....	CO ₂	5.76
Water.....	H ₂ O	5.65
Organic Matter.....		3.50
Graphite.....	C	trace
Manganese.....	Mn	trace
Total.....		99.62

The part of the specimen from which this analysis was made was evidently more altered than that from which the section was made, as is shown by the great decrease in the amount of magnesite, and the corresponding increase of the iron oxides and the iron-bearing silicates. As an explanation of this it may be said that while the fragment from which the section was cut was within $\frac{1}{4}$ inch of the contact, that from which the analysis was made was a layer, one side of which formed the contact itself; and the change must be attributed to the intimate proximity of 53-1, the siliceous and ferruginous representative of the iron-bearing member.

Conclusions: In 53-1, 39, 37-B, 37-A, 36 and 35, we have a fine series illustrating the processes of change, and reaching almost from one end of the typical scheme of development to the other. The chief motive has been the process of decomposition and concentration under the influence of a moderate amount of atmospheric agencies, the goal being the greatest possible stability under these conditions. Attendant on this there has been the introduction of a more unusual factor, due to the proximity of the rock to the overlying calcareous beds,—the infiltration of xenogenous carbonates. This attendant circumstance has modified the action of the governing motive somewhat, but the two remain sufficiently distinct for their results to be separately noted.

Section 53-1 shows many angular fragments, hardly yet broken apart, of the firm mass of chloritic matter, with finely disseminated iron oxides and other ferruginous materials. This chloritic matter must for the present be regarded as the primary rock of the series. That the brecciation has occurred without any considerable carriage of the fragments from their original positions

is shown by the fact that the fragments fit closely together, are yet connected in many cases, and are never rounded. Around the edges of the granules, the combination of this silica with the original substance produced a broad border of secondary minerals.

39 appears to be directly derived from 53-1, by a process of oxidation. The original fragments of the chloritic substance have become nearly opaque from the formation of hydrated iron oxide. The small decomposition bodies of 53-1 have been extended, till they often fill up the whole of the intergranular space. These decomposition areas, instead of being pure white calcite as in 53-1, are light green, mottled with brown, and are made up of an intimate mixture of the carbonates, limonite, actinolite and silica. The rounded grains of carbonate have also been decomposed, till only a small portion of the original grain remains in the middle. When this process goes on a little further the original grains will be quite obliterated, and a somewhat homogeneous mass of decomposition products will remain.

In 37 we find that the decomposition has gone on till the chloritic substance has almost entirely disappeared, and is replaced by iron oxides and silica, which still mark the outlines of the granules. Usually the iron oxide has been leached out and scattered through the section, or concentrated in places, leaving the granules marked by the finer and clouded silica alone. The iron when concentrated has sometimes become crystalline, and has passed from the earthy form to the magnetic state. In 36, the process has still further proceeded. The outlines of the granules have become indistinct. This has resulted from the concentration of the little remaining iron oxide in them, and also from the partial crystallization of the fine cryptocrystalline silica, which has passed in some cases into the phenocrystalline condition, and so cannot be distinguished from the silica of the interstitial spaces. In 35 we have a still more advanced stage. The granules are with difficulty made out, even in the most favorable places; the silica has become predominantly phenocrystalline; the iron has been further concentrated, and has begun to arrange itself into rude bands along the lines of greatest weakness in the rock; and the rock resembles more the typical "jasper" of the iron region than anything else.

The infiltration of xenogenous carbonates has had a peculiar but independent effect. They have scarcely penetrated 39, and

so there are no results here. In 53-1 they have probably supplied the carbonate rim around the granules. In 37 they have produced the differentiation between 37-A and 37-B, and have collected in the more open parts of 37-A. The effects of this impregnation are more clearly seen in 35 and 36, when oxidizing agencies have attacked these carbonates, and from them formed centres of disintegration scattered everywhere through the rock, which, ever growing larger, soon give it a curious pitted and honeycombed appearance, and when carried to the extreme produce the decomposition of the entire body.

GROUP FROM SECTION 10, T. 58-19.

The principal specimens in this group—149, 150 and 151,—are from the same pit.

SECTION 149. In hand-specimen yellow; varies from a flinty texture to soft and crumbling. The harder spots of grayer material are residuary fragments. Fracture somewhat conchoidal; a distinct faint banding. Under the microscope there is a lighter residuary fragment, and a darker portion. *Variety 1*, the residuary fragment, has a somewhat distinct convex boundary. It consists of a fine background of cryptocrystalline silica, through which are disseminated clusters or individual crystals of actinolite, and some iron oxide dust. *Variety 2*, which surrounds variety 1, differs chiefly in the presence of a larger amount of actinolite and iron oxide, the latter becoming especially important. The result is that the section is in places quite opaque. There is a tendency to a linear arrangement of the materials. Both varieties, but especially 2, are traversed by numerous cracks. *Conclusion*: 2 differs from 1 by virtue of having been more cracked and strained mechanically, and so acquiring a more distinct set of sometimes parallel lines of weakness, which allowed freer access of percolating waters, and have brought about a more complete impregnation with iron oxide. Both 1 and 2 are in an advanced stage of metasomatic change, and the process may well have been hastened by the movements in the rock.

SECTION 150. In the hand-specimen roughly banded. In the middle is a residuary, white, granular, somewhat porous rock, of irregular fracture. This passes on both sides to a fine, brown, flinty rock, like 149, and this rock in turn is weathered on one side to the depth of a quarter of an inch to a blood-red pulverulent rock, partly of earthy hematite.

SECTION 150-A is cut from the light, granular rock, which may be called variety 1, and is just beginning to grade to the brown, flinty rock, or variety 2, on the edges.

Variety 1 consists of a background of cryptocrystalline silica, in which the traces of the spotted-granular structure can be distinctly made out. The granules are distinguished chiefly by the finer grain of the silica, as compared with that of the interstices; and also by scattered patches or solid cores of earthy hematite, and very minute fragments of actinolite (?) and chlorite (?). The interstices between the granules have been to some extent impregnated with impurities. The patches of earthy iron oxide which occur in the granules have often been in part or wholly washed out, leaving the rounded pores characteristic of certain parts of the hand-specimen. There is evidence of a stretching parallel to the general banding of the rock. This is shown by the tendency for the granules to arrange themselves with their longer axes parallel, as if pulled out of shape by a common force; and also by a breaking apart of some of the iron oxide patches, forming fissures which are perpendicular to the general direction of the tension.

Variety 2 is marked by a linear structure. That these lines represent planes of special weakness is shown by the impregnation of the rock near them by earthy iron oxide. When there is no such impregnation, the spotted-granular structure is found to be more nearly effaced along these lines than anywhere else in the rock. The impregnation gives the rock its brown color, and of course hides the spotted-granular structure. A considerable quantity of cloudy, decomposing siderite in scattering and very small masses is present. It seems to be a late decomposition product, for it is nowhere concentrated and occupies no definite place. It is often associated with, but not confined to the granules, in the main body of the rock; and in the impregnation bands it is closely associated with the hematite or limonite. Its presence seems to indicate the process of impregnation as follows: In a part of the rock more or less removed from this specimen, the iron was taken into solution by slowly filtrating aquæous agencies as a carbonate. Part was deposited through the rock as carbonate, but most found its way to the weaker lines, and there, under stronger oxidizing influences, was precipitated as the sesquioxide, usually hydrated.

SECTION 150-B. Contains variety 1 and variety 2. Variety 1 is more changed than in 150-A. The spotted-granular struct-

ure is fainter, and the materials are more or less arranged in lines. In separated irregular lines iron has been concentrated, and is now chiefly in the form of martite, in which the cores of the original magnetite still frequently remain. Variety 2 is quite opaque at its contact with 1,—a proof that the difference between the two originally arose from a curving crack, from which the mineralizing solutions leaked down into the rocks below, forming 2, while it left the rock above, or variety 1, little altered. As the distance from this original fissure increases, the quantity of iron oxide steadily diminishes, and it soon becomes quite translucent. The fact that the iron is an impregnation is then plainly seen. In parts a fine network of earthy oxide can be seen surrounding the grains of silica.

Conclusion: The band of martite in 1 is an impregnation from a fissure. That at the contact of 1 and 2 was the same. From this latter the iron penetrated downward, forming variety 2. The process is evidently a replacement of cryptocrystalline silica by iron.

SECTION 151. Like variety 1 of 150-A and 150-B, but less altered than either,—the least altered rock of the series. Structure spotted-granular. The granules are distinct, and show little alteration by stretching. Their outlines are usually subangular. Most of the iron oxide that formerly occupied them has been dissolved away, except perhaps in rims around the edges, thus giving rise to the porous, honey-combed structure which is a peculiar feature of the hand-specimen. Some few of these granules which are made up chiefly of earthy iron oxide still remain intact; others have had the iron half-dissolved out; and from this to the empty pore there are all stages. Most of the granules which remain unaltered, however, are those which contain a predominance of silica instead of iron. This silica is somewhat coarsely cryptocrystalline, and is usually sparsely impregnated with hematite, limonite and siderite. On both sides of variety 1 are bands of variety 2. These bands curve so as to nearly meet, and are seen to follow fractures. The process is seen to be simply impregnation, as above described, without any discernible mechanical straining other than as shown in the fractures themselves. These bands represent the field in which filtrating chalybeate waters met the oxidizing agents, which penetrated inward from the fractures, and where the iron was thus precipitated in the rock.

Conclusion: A spotted-granular rock, advanced in change, consisting chiefly of iron in the granules and cryptocrystalline

silica in the interstices, has been subjected to slight mechanical pressure, resulting in parallel strains of varying intensity. In some cases the effect was sufficient to produce the obliteration of the spotted-granular structure, the development in its place of a slightly schistose arrangement of the minerals, and the crystallization of a small amount of actinolite. Section 149, variety 1, shows this. Usually there was no such effect, and the strain produced only an irregular cracking. In other cases still, the only result was a general weakening. Subsequently waters, coming into the rock, rendered accessible by these accidents, removed the iron from some places and concentrated it along the lines of weakness in bands and along the weaker zones as impregnations.

GROUP FROM SECTION 2, T. 58-18.

The members of this group, numbers 72, 74, 78, 79 and 80, are all from a single shallow pit in the northwest of the southwest of section 2, T. 58-18.

SECTION 72. In the hand-specimen, this is seen to be coarsely brecciated, the fragments being of black or red chert, and the matrix a spotted-granular rock. The section is so cut as to include a portion of the matrix, and of two of the large fragments. The larger of these fragments is composed partly of dark gray, and partly of reddish chert, and the smaller is entirely of the reddish variety.

The matrix, which may be called *variety 1*, resembles 65 and 74. The rock is composed of silica, magnetite and hematite, their relative abundance being in the order named. The granules are rounded or subangular, and are closely crowded together. In them the magnetite sometimes has crystal boundaries; but generally it has none. The hematite is earthy. Around certain bodies of magnetite there are concentric rings of magnetite and silica, which may be truly concretionary, but from their irregular, often non-persistent course, they are more probably phenomena attendant upon the oxidation and consequent contraction of an original siderite, the stages of which process have been more fully worked out in other sections, and will be described later. Briefly, an original mass of siderite oxidizes on the periphery to hematite. The loss of volume entailed in this change results in the contraction and the development of a more or less perfect fissure between the outer rim of hematite and the main body of sider-

ite. This crack is then filled with silica in solution from the surrounding rock. This takes place repeatedly, the fissures becoming less and less pronounced as the volume of the contracting carbonate becomes smaller, till finally there is no parting produced. A subsequent deoxidation of the hematite to magnetite gives the exact structure that we now find in the rock. The siderite still remains in this section in considerable quantities, and the process described can to some extent, be seen to be still going on. This carbonate is in the form of irregular cloudy masses and grains in the interior of the granules. In some it constitutes the main part of the granule; usually it is somewhat replaced by silica, and appears only as irregular residuary grains; sometimes it has entirely disappeared. These bodies have generally magnetite and hematite rims. Blood-red earthy hematite occurs constantly as a decomposition product, in some cases of the magnetite, in others of the siderite. Thus it may form the rim of a body in which siderite, with silica, occupies the centre; or it may constitute part of the centre of a granule of which magnetite forms the rim. By oxidation of both magnetite and siderite, and staining of the silica, it comes to be uniformly distributed throughout the whole body, and these blood-red granules are the most common variety in certain parts of the section.

Variety 2. The larger fragment. The line of separation between this and the matrix is quite distinct, yet in most of its area it retains traces of a spotted-granular structure which clearly resembles that of the surrounding mass. The boundaries of the granules are not so well marked, and they have been distorted so that the longer axes are apt to lie in a common direction, and parallel to numerous wavy and shadowy lines which mark the change that has taken place in the rock. The darker part is made up of finely comminuted and indiscriminately mingled cryptocrystalline silica and dust-like iron oxide. In the red part, which shades off gradually from the darker part, the iron oxide has concentrated itself to some extent between the grains of silica, thus forming a rude network. The silica grains are also slightly enlarged. The massing of the iron oxide gives bodies of it large enough to reflect the light, and this gives this part of the rock its red color. Both the black and the red parts of 2 are traversed by veins of cryptocrystalline silica, which do not extend into the matrix, and are nearly at right angles with the general parallel structure.

Variety 3. The smaller fragment. The outline of this is rounded. It has the spotted-granular structure much better preserved than has 2. The outline of each of the granules is very clear, but on the whole is much fainter than the corresponding lines of the matrix. The silica is more finely divided, and the iron oxide is scattered as dust through the section, or concentrated into bunches large enough to give a reddish color to the rock. There are no lines of shearing observable.

Conclusions: A spotted-granular rock is seen to have undergone metasomatic changes, by which the granules were altered by change of siderite to hematite, and this to magnetite, with some attendant introduction of silica. In the course of these processes a strain developed in the rock which culminated in a shearing motion of the weakest zone, which produced bands of more or less schistose and altered rock. A continuation of this motion produced a slow breaking up of the bands and a slight separation of the fragments. (The fragments are still arranged in irregular bands.) After this accident, metasomatic changes continued, giving to the fragments their red color, and in the matrix continuing the processes already begun. Compare specimen 27, whose history is very much the same, except that this has escaped the actual fracturing of the bands. In specimen 73, which is from the same place as 72, and is similar in every respect, a sideritic chert is seen to constitute the core of one of the larger fragments, the outside of the fragment being a reddish chert as in 72, and the matrix being as described above. This is evidently a further continuation of the process of concentration subsequent to the complete intermingling of the materials by shearing, which in 72 is most developed in some parts of variety 1.

The powdered rock 72 gave little reaction with cold dilute hydrochloric acid, but on warming afforded an abundant effervescence of carbon dioxide.

SECTION 74.—Like 65, both in hand-specimen and slide. The decomposition proceeds from certain centres in the rock, thus giving a pitted appearance. Under the microscope, as well as in the hand-specimen, it is seen to have a distinct spotted-granular structure, and generally is coarsely brecciated as well. The silica is very finely divided and might be classed as cryptocrystalline to apparently amorphous. Its appearance throughout the whole section suggests incipient disintegration. The decomposition-pits have irregular boundaries, and a border which is quite dark under crossed nicols. This border is a

finely mixed aggregate of the ferrous and siliceous ingredients of the rock, in minutely small particles. The leaching out of the iron leaves the white powder which is seen to line these pits in the hand-specimen. The process of disintegration of cryptocrystalline silica to an extremely fine powder, under atmospheric agencies, is finely shown in this specimen. The general structure of the rock, where not decomposed, is like that of the matrix of 72.

SECTION 78.—In the hand-specimen a dark-gray ground-mass, mottled with red granules; fracture conchoidal; prismatic jointing; no cleavage. Under the microscope, the granules are strongly marked, but are in an advanced stage of metasomatic change. They are composed of iron-oxide in the form of earthy hematite or limonite, either in masses or distributed through the silica; their outlines are rounded; they are separated one from the other by some distance; and occasionally they become confused with the ground-mass. In these cases the finer grain of the silica, as seen under crossed nicols, usually distinguishes them. Magnetite occurs sparingly, either as residuary cores in the granules, which occasionally make up the most of their bulk, or as small crystals in the ground-mass of silica. Hematite is found only in the granules, in which it occupies a part or the whole of the space, and occurs with or without the residuary cores of the magnetite from which it is evidently a decomposition product. In its later stages of change, it is dissolved and replaced by silica, and this process goes on till only a staining remains to show the presence of the iron, the rest being entirely of silica. Finally even this disappears, and the granule at times becomes confounded with the intergranular material. Siderite is an important mineral in this rock: it is distributed in such a way as to make the rock a transition stage between the common massive spotted-granular rock and a sideritic chert. It is found on the edges of the granules, in irregular masses, evidently a decomposition product of the hematite, which generally forms a residual core. Often the core is of both magnetite and hematite. In this case the magnetite may form the residuary core for the hematite, showing that at first the conditions of oxidation were freer, permitting the change from the magnetitic to the hematitic state, and that subsequently a partial withdrawal of the supply favored the change of both magnetite and hematite to the sideritic state. Siderite also occurs in small crystals in the ground-mass. Here it often encloses some of the larger

silica grains around which it has formed, and the successive crystal outlines which mark the stages of growth are plainly seen. Thus this siderite, like the magnetite of the ground-mass, is of a segregationary origin. It is evident that, as this process goes on, with the change of the remaining magnetite and hematite into siderite, the concentration of this siderite to make larger these tiny crystals, and the rearrangement of the silica in consequence, that the spotted-granular structure will be obliterated, and a chert, containing large crystals of siderite, will result. (See Plate VII, Fig. 1.)

SECTION 79. The specimen from which this is taken is an extremely brecciated mass. The section is cut from one of the larger fragments of the rock. It is of chert, which in its hard parts is banded with alternating fine gray and white lines, and in other places is decomposing to a white powder. Many of the smaller crevices between fragments of this nature are filled with translucent crystalline quartz, of the variety that is commonest in quartz veins. This shows that when the brecciation took place the rock was in a dry, hard condition, and, as a consequence, gaping crevices were left between the crushed and broken fragments. These crevices were subsequently filled by quartz from freely percolating waters, in the same way that ordinary veins are formed.

Under the microscope, section 79 is composed of finely comminuted silica and iron oxide dust. The iron is to some extent concentrated into bands, some shadowy and microscopic, others coarser. The coarser ones follow fractures which traverse the rock. The oxide is chiefly magnetite mixed with some hematite and limonite, and this gives the black color to the bands.

Conclusion: This rock has the same origin as the larger fragment of section 79, except that the shearing has been more violent, producing certain lines of weakness along which the iron afterwards was concentrated, instead of uniformly through the rock. In the hand-specimen some of the other fragments are seen to still preserve a distinct spotted-granular structure, but to be otherwise quite like the fragment that has been described.

SECTION 80. In the hand-specimen, a breccia like 79. Under the microscope it is a much-broken mass, the fragments of which are made up of silica, calcite and other carbonates, and the iron oxides, in various proportions. The mass appears to have been originally composed mainly of silica and the iron oxides, but at the time of its brecciation it has been thoroughly

wrenched and cracked. There followed the infiltration of calcite, forming veins and impregnations, and combining with the elements already present to form a large number of confused secondary products. In some spots the rock is almost pure calcite.

GROUP FROM SECTION 6, T. 58-17.

In this group are included sections 82 and 83, with hand-specimen 70. They are all from the same pit in the southeast of the northeast quarter of section 6, T. 58-17. This pit was explored with the diamond drill, and so to a much greater depth than those which have been described formerly. Below the glacial drift the first thing encountered was a thin conglomerate, composed almost exclusively of fragments from the iron-bearing member, and greatly decomposed. This was supposed to be of Cretaceous age. The base of this was a lignitic swamp deposit, connected with and apparently of the same age as the conglomerate. This rests upon a porous, friable, finely pulverulent deposit, strongly resembling a consolidated kaolin. Typically it is a pure white, but when stained with iron oxide it becomes banded with red, yellow and brown. This deposit is eighty feet thick, and at the bottom it passes gradually into a harder and firmer, although somewhat decomposed rock. This rock was passed through to the depth of over two hundred feet and the drilling was stopped while yet in it. Specimens 82 and 83 are from the hard rock, very near one another, at a depth of about 180 feet from the surface; specimen 70 is from the soft white pulverulent deposit.

SECTION 82. Hand specimen of a dark gray color spotted with red and white; fracture conchoidal. Under the microscope it has a spotted-granular structure, but is advanced in metasomatism. The granules are distinguishable by rims or internal fragments of magnetite, earthy and micaceous hematite, and limonite, and by the very fine cryptocrystalline nature of the silica. The interstices between the granules are of fibrous chalcedonic silica, with sometimes the exception of a small space in the very center, where there are grains of phenocrystalline quartz. The fibrous chalcedony shows in places a disintegration into a very finely divided granular state, much resembling the silica of the interior of the granules. It is evidently this that gives the powdery white appearance to certain parts of the rock, and with the completion of the process and the leaching out of the iron, finally results in the transformation of the entire rock to the consolidated white powder.

SECTION 83. In hand-specimen, this is, in general appearance, like 82. The color differs, however, in that the ground-mass is light green instead of dark gray, and that the granules mainly appear black instead of red. Under the microscope the iron is seen to be less in amount than in 82, and occurs as crystalline masses of magnetite. The granules and the interstices, to a less degree, contain a light green finely disseminated chloritic substance. The silica is about the same in general, but in places more coarsely crystalline grains are observed. Both 82 and 83 crumble easily under the hammer to a fine gray or white powder.

SPECIMEN 70 is a consolidated fine white powder, with a greasy feel. It can be easily cut with a knife into any desired shape. It is mainly white, with frequent bands of brown or light red. That these bands are later in origin than the reduction of the rock to its present condition, and result from the precipitation of iron oxide from infiltrating waters, along the weakest zones, is quite certainly shown by a study of this and other specimens from the same place. For while the bands are in general beautifully distinct and parallel, yet they take advantage of any weaker line which offers, whatever the direction, and offshoots from the main band may be found, striking off at any angle, and generally terminating blindly. This material was at first supposed to be a kaolin, and later, from its evident origin and by analogy with other powders of like nature, but developed on a smaller scale, it was suspected to be a silica powder. An analysis was made of the white portion of the rock with the following result:

ANALYSIS OF NO. 70 (CHEMICAL SERIES NO. 238) BY C. F. SIDENER.

Silica.....	SiO ₂	77.89 per cent.
Alumina.....	Al ₂ O ₃	13.55 " "
Sesquioxide of iron.....	Fe ₂ O ₃	1.83 " "
Lime.....	CaO	trace.
Magnesia.....	MgO	.36 per cent.
Potash.....	K ₂ O	.84 " "
Soda.....	Na ₂ O	.58 " "
Water.....	H ₂ O	4.45 " "
Total.....		99.50

This analysis shows the rock to be mainly a pure silica powder, with a large amount of the hydrous silicate of alumina, or kaolin; a very small residual portion of the decomposed and leached iron oxides, here evidently in the form of the hydrous

sesquioxide; and small amounts of the calcium, magnesium, potassium, and sodium which entered into the composition of the rock from which this was derived.

Conclusion: In this group 83 is evidently the primary rock. It also stands in the first part of the typical series of change. In it the granules are closely packed together, and are made up in large part of the green chloritic substance. The silicification of the chloritic substance may be seen to be going on, as described and observed more fully in specimen 217, (p. 84). In section 82, the granules are smaller and more rounded, and the chloritic substance has disappeared, attended by a proportionate increase in the silica. The silica is somewhat finer than in 83, showing the effects of disintegration, and this process is plainly still going on. In 70, the rock is entirely decomposed to a fine white powder, which consists of free silica and silicate of alumina, with trifling amounts of the other elements. These ingredients result from the decomposition of the greenish silicate of 83, which has produced the separation of silica and the leaving of a residual clay. The more soluble decomposition products, including the iron, have been leached out from this residual clay, leaving mainly kaolin.

82 may be compared with 125 and 39, and 83 is nearly identical with 166.

GROUP FROM SECTION 22, T. 58-20.

The members of this group are sections 213, 215, 217, 219, and 220. Of these 213 and 215 are from one pit, and 217, 219, and 220 are from another about twenty yards distant from the first. These pits are in the northwest quarter of the northwest quarter of section 22, T. 58-20.

SECTION 213. In hand-specimen, mainly a dark brown rock, heavy with iron, and with somewhat of a metallic lustre. There are also scattered residuary blotches, streaks, and patches, of a pinkish-white rock, mottled with red. These patches exhibit faintly the spotted-granular structure. On one side of the specimen is a body of white, finely crystalline silica, about $2\frac{1}{2}$ inches in length and $\frac{3}{4}$ inch wide, which appears to be the filling of a cavity that resulted from some movement in the rock, or possibly from decomposition. In places, oxidation has changed the brown rock to some depth, producing a deeply pitted surface, coated with brown and yellow powder. This seems to follow a rough parting plane in the rock. In

other places the decomposition has been more slight and serves to bring into prominence the spotted-granular structure of the rock, by dissolving out the interstices. This leaves the harder granules, with empty spaces between, like an aggregate of sand grains. This, it will be observed, is the reverse of the usual effect of decomposition, for in general the granules are the first to yield, and the result is that the rock becomes filled with rounded pores. The constantly changing character of this rock, both mineralogically and structurally, sufficiently accounts for this. There is a distinct jointing on two sides of the specimen, marked by smooth surfaces, in addition to the rough horizontal parting described above. These joint-planes if produced, would intersect each other at an angle of about 60 degrees. Under the microscope, 213 has in its least altered portions, which represent the lighter residuary patches of the hand-specimen, a spotted-granular structure. The granules contain various scattered and fragmental forms of iron—magnetite, earthy and micaceous hematite, and siderite. The darker portions of the rock differ in composition only in the relative proportion of the different minerals. There is a marked increase in the amount of iron minerals, which varies from about 10 per cent. in the lightest parts to perhaps 60 per cent. in the heaviest bands. Magnetite and hematite (both earthy and micaceous) are present in nearly equal amounts. The magnetite is in small masses with ragged boundaries, surrounded by the other forms. The hematite is mainly associated with the magnetite in such a way as to show its derivation from it. Siderite is another plentiful ingredient, and also an apparent decomposition product of the magnetite. In one place a complete pseudomorph of siderite after a cluster of magnetite crystals is seen. The distribution of the three forms of iron is such as to indicate the following order: 1. A change of the original magnetite to siderite. 2. The oxidation of both magnetite and siderite to hematite. The silica of the ground-mass varies from finely to coarsely cryptocrystalline.

In structure the darker portions differ from the lighter in the obliteration of all traces of the spotted-granular structure, and in the development of certain roughly parallel planes of mechanical disturbance.

Conclusion: A spotted-granular rock has been subjected to some strain, which probably arose from contraction of volume in the processes of change. This contraction has produced without doubt the smooth vertical jointing, and probably also

the rough horizontal parting. Microscopically, it has resulted in the roughly parallel cracks, and the lines of special weakness, which run around the unchanged lighter parts. There is no microscopic or macroscopic schistosity, to indicate any lateral slipping. Following the weakening of the rock there has followed the oxidation of the magnetite to siderite and hematite, its concentration in the zones of greatest weakness, and the consequent obscuring or obliteration of the original structure. It is to be noted that the siderite in this and in many other sections surrounds the magnetite as a decomposition product, and is cloudy and without crystal form. It thus comes under the group of decomposition products from magnetite called *leucoxen*. Rosenbusch describes it as an alteration product of ilmenite, titaniferous magnetite, and rutile. Concerning its nature he says:* "Its chemical composition is not the same in all cases where it has been investigated, and has been considered the equivalent of a variety of minerals (titanite, anatase, and siderite) by different observers." In every case where this mineral is present in these rocks, chemical tests show it to be siderite, and no signs of titanium can be found either in it or in the magnetite whence it is derived. The existence of this leucoxenic decomposition product surrounding magnetite has sometimes been held as sufficient evidence that the magnetite was titaniferous, but it is clear that it is not necessarily the case.

SECTION 215. In general appearance like 213, from which it differs in that some of the lighter spots are pure white, and the darker parts are more fine-grained. Under the microscope the rock is like 213, also, but there is no trace of the spotted-granular structure. The mineral constituents are scattered irregularly around. Conclusion: This is nearly identical with 213, but shows a slightly further advanced stage of change, resulting in the effacement of the granules, the scattering of the minerals, and a greater development of secondary products.

SECTION 217. This is nearly identical, both macroscopically and microscopically, with 125. In the hand-specimen it is dark green, very faintly spotted and contains small blotches, bands, and spots of magnetite. There is an irregular jointing, but no cleavage; the fracture is conchoidal; the specific gravity rather high. Under the microscope, the spotted-granular structure is well shown. The granules are rounded, subangular, or irregu-

*Microscopical Physiography of the Rock-Making Minerals. By H. Rosenbusch. Translated by Joseph P. Iddings. Second, revised edition, p. 165.

lar, and are closely crowded together. They consist mainly of the compact green chloritic substance described in 39, 125, and other slides, together with actinolite, magnetite, hematite, and siderite. Magnetite, in very small crystalline grains, and with associated hematite, is usually scattered sparingly through the granules, but is in places concentrated as described in the hand-specimen. The process of granular-brecciation is seen to be going on in some parts of the section, where the large, angular granules are sometimes cracked and seamed by fissures of varying width; sometimes separated into distinct smaller granules by an enlargement and continuation of these fissures; and again further separated and rounded, but their general outlines continuing such that they nearly match one another.

The green chloritic mineral has never any crystal outlines, but it encloses crystals of magnetite, and in places, under high power, it is seen to contain many very minute clusters of pale-green, pleochroic actinolite. It is slightly pleochroic, varying from lighter to darker green, and often shows an irregular cracking. In places this mineral occupies the whole of the granules; in others it becomes filled with silica in spots and fissures; then it is reduced to form a kind of network around the silica; and finally the granule is composed almost entirely of silica, with only a few dust-like grains, giving a cloudy greenish appearance, to mark the existence of the chloritic substance. From the chloritic granules to the siliceous granules there is every conceivable gradation, and one runs into the other so that it may be seen to be a process of metasomatic change. In the freshest phases the chloritic substance is marked only by a slight mottling of lighter and darker green. Soon, however, there appear scattered through it curious small dark rings. By nice adjustment under a high power the real material of the ring is seen to be a very narrow band of transparent silica. It is extremely fine, and varies from an apparently amorphous to a finely cryptocrystalline or chalcedonic nature. The number of these rings rapidly increases in the next stage, till the whole surface is covered with them. They grow larger, too, in both directions, so that on the outside they meet and unite, forming compound rings, and rosette-like forms, and, on the other side, the material inside the ring becomes smaller. It also becomes darker in color than at first, apparently from a growing excess of iron, in some cases becoming quite opaque. In the next stage the change has gone on till the silica has usurped most of the space

in the granules. The chloritic substance, grown darker and nearly opaque, forms a compact network around the silica. The chloritic centre of the rings has in most cases disappeared, in others is represented by a very small patch of ferruginous clayey material. By this time the silica has often assumed a distinctly chalcedonic nature. It is usually made up of fibres that radiate from the inner core of the ring, or if this has disappeared, from the centre of the circle, and terminating at the circumference. In proportion as the circle grows larger and tends to unite with others this fibrous structure becomes obscure and passes into a semi-crystalline condition, in grains that have an undulatory extinction and low polarization colors. In the last stage the chloritic substance has disappeared, and the silica occupies the whole granule, except for the cloudy residuum which gives it a color sufficiently distinct to contrast strongly with the colorless silica of the interstices. The silica at this time is semi-crystalline, semi-chalcedonic. Only occasionally are the traces of the fibrous arrangement met with, and yet there is no firm crystalline structure. There seems to be a tendency, however, for each of the original rings to form, when crystallized, a distinct grain. There may be found single granules which represent each a stage of the process of change described, but usually all the stages are seen going on in the same granule, passing from the nearly pure chloritic substance to nearly pure silica. Actinolite forms a small part of the section, perhaps 5 per cent. It seems to be invariably of secondary origin, since it is found chiefly around the edges of the granules, from which the crystals radiate into the intergranular spaces. (See Plate VI, Figs. 1 and 2).

Although the chief method of silicification of the granules is by the process described, there is an important auxiliary. In many cases silica which is probably foreign to a granule penetrates along cracks which have been produced by some movement in the rock, and enlarges them by wedging and by replacement of the wall-material; and in this way continually divides the granule into fragments. Cracks which traverse the whole rock, on the other hand, usually give rise to impregnation veins, along which chiefly magnetite, with some hematite and calcite, is concentrated.

That the silica which takes the place of the chloritic substance is formed from its decomposition, and not from replacement, is shown by the method of distribution of the change, in that it does not begin at the periphery or in mechanically

weak places, but appears simultaneously in all parts of it; so that portions remote from other silica and outside influences are quite as much affected as any. Moreover, the separation of earthy iron oxide, coloring the remaining chloritic substance a dark brown, is proof that a decomposition has actually taken place.

Conclusion: This rock is near the beginning of the typical series of change. As in other similar sections, the original rock seems to have consisted chiefly of a chloritic substance. In the decomposition of this substance there has resulted the separation of free silica together with iron and the more soluble salts. These soluble materials were almost totally leached out; the iron, less soluble, was taken into solution and mainly deposited near by, and is represented by bands and blotches of considerable size and frequency. What few carbonates are scattered along the microscopic impregnation veins are probably also derived, through this change, from the original green chloritic substance. They are chiefly calcite, probably magnesian. The processes observed in this rock, it will be seen, have gone on under conditions of comparative freedom from modifying highly oxidizing forces. Had the supply of these been somewhat greater, and yet not great enough for complete oxidation, the iron would have separated as carbonate, and in this form would have occupied more of the bulk of the rock. This carbonate would probably be afterwards replaced by silica, by reason of its greater solubility. In the rock under consideration waters bearing carbonic acid had slight access, and so separated silica is the most noticeable result of this change. It is this silica, taken into solution and carried down into the rock below, that would in turn replace the carbonates formed under our suppositious conditions.

An analysis of this rock gave the following results:

ANALYSIS OF 217 (CHEMICAL SERIES NO. 241).
BY ALONZO D. MEEDS.

		Per Cent.
Silica.....	SiO ₂	56.28
Sesquioxide of iron	Fe ₂ O ₃	15.25
Protoxide of iron.....	FeO	18.28
Alumina.....	Al ₂ O ₃	3.29
Lime.....	CaO	.93
Magnesia.....	MgO	.72
Soda.....	Na ₂ O	.25
Loss on Ignition		4.75
Total.....		99.75

It must be remembered that this analysis is independent of the iron which has been concentrated into spots and bands.

Its place has been filled with silica. Nearly all of the iron which has become separated by decomposition of the silicates has been removed in this way. In any attempt to estimate the exact composition of the original rock this must be reckoned, and the corresponding amount of silica deducted.

SECTION 219. In the hand-specimen, this closely resembles 217. There are scattered all through it, however, small grains which show pearly crystal faces, and give abundant effervescence of carbon dioxide with cold dilute hydrochloric acid. There is also some pyrite in disseminated crystals. Under the microscope, the chloritic substance, inclosing magnetite, is substantially as described for 217. The peculiar features attending the separation of silica are not quite so well shown, however. The magnetite sometimes is almost entirely changed to earthy hematite; the interstitial silica is coarsely chalcedonic. Around the margins of the granules a fibrous fringe of silica is arranged, and when the intergranular space is narrow, these fringes meet in the middle. Where it is larger, as where three meet, there is a space in the middle where the grains are coarser, and approach a crystalline phase, though they rarely give any polarization colors. Fully 30 per cent. of the section is composed of large crystalline grains of calcite, which shows perfect cleavage, but has allotriomorphic outlines. This has penetrated the rock and crystallized both in the granules and in the interstices; when it penetrates both, it obscures to some extent the spotted-granular structure.

Conclusion: The habit of this calcite makes it clear that it is not a secondary product, but is xenogenous. Its source was probably from the altered limestone beds which overlie the rocks of the iron-bearing member. The occurrence of pyrite shows the presence of sulphuric acid, as well as lime, in the waters. The existence of this acid in a rock which shows such profound decomposition of its silicates has some additional significance, as we shall see later.

SECTION 220 is nearly identical, both in the hand-specimen and in the slide, with 213 and 215. Faint traces of the spotted-granular structure may be observed, but could not with certainty be identified by this slide alone. The silica is very finely cryptocrystalline. The iron and dark ferruginous secondary products form a network of irregular shape and distribution. Some of this is magnetite, in small grains, but the most is a micaceous hematite, with limonite; and some actinolite, which is stained dark red by impurities.

Conclusion: In this series 217 is evidently the least altered phase. 219 is essentially the same thing, but is altered by impregnation of calcite and pyrite. From this 213, 215, and 220 are derived by exposure to oxidizing forces. There is no evidence of any auxiliary dynamic action, even of that common kind provoked by the metasomatic changes themselves. The result is a rock without definite structure, composed of cryptocrystalline silica and scattered iron oxides and secondary products. In other words, nearly the whole length of the typical process of change separates two specimens within a few feet of each other, which we must believe to have originally been identical; and the only agent in this change which we can discern is the common atmosphere.

GROUP FROM THE MOUNTAIN IRON MINE.

The members of this group are sections 97 and 232, and specimen 204. The ore body of the Mountain Iron mine lies in a depression from which the land rises to the north, east and west, while on the south it passes by a gentle slope into the lower country. On the north, there rises almost directly from the low-lying ore-body a steep bluff, on the face of which are outcroppings of hard siliceous rock, banded with hard ore. These outcrops are of especial interest, since they were among the first traces of the iron-bearing rock known on the Mesabi, and although they were repeatedly examined and adversely reported upon, yet doubtless they gave the motive to the search which finally resulted in such signal success. Specimen 97 is taken from this outcrop. Specimen 204 is taken from a mass of hard ore which was found surrounded by soft hematite, in the process of mining. That this is a residuary fragment, representing the former state of much of the rock which has since been changed to form the soft ore, cannot be doubted. In shape it is irregular, with ragged outlines made by the decomposed and crumbling surface. It is probably about four feet square by two feet thick; in its inner parts it is a hard, gray, porous rock, apparently of hard hematite, but probably siliceous; but it grows softer towards its periphery, till it passes into beautiful purple, yellow, brown and red soft ore. Specimen 232 is from a pit near the mine, which encountered no ore.

SECTION 97. In the hand-specimen, this is red and crystalline, and is coated with a thick layer of botryoidal limonite. Under the microscope, it is seen to be mostly composed of

crystalline quartz, in large and small angular fragments. This rock presents evidence of having been broken, strained, and shivered in a most remarkable manner. The resulting cracks have served for the introduction of crystalline limonite, which has here segregated in minute veins and has to some extent impregnated the quartz. This gives the light red color to the rock. *A certain constant direction of the fissures, indicating a single strong fracturing force, moving only in one direction, is seen throughout the rock.* The importance of this will be seen later, in the discussion of the origin of the ore-deposits. This rock presents none of the commoner features of the iron-bearing rocks. It is simply a crushed and fractured mass of crystalline quartz, in which no individuals are distinguishable, no granular structure or crystalline outlines; and this quartz is stained with limonite. From the general appearance of the rock, and the plentiful incrustations of limonite in fissures and on the outer surfaces, it is quite safe to conclude that the iron is idigenous, and is but a remnant of the amount that was originally in the rock. The rest has been entirely removed through the channels for percolating waters opened up by the profound fracturing.

SECTION 232. The hand-specimen shows three distinct varieties, one derived from another. The first is nearly white, shaded to gray. It is apparently homogeneous, of granular texture, and irregular fracture. It appears to be identical with the lighter residuary portions of 213, 215 and 220. This is stained brown by iron oxide to form the second variety, which surrounds the first, leaving it as irregular residuary fragments of all sizes. The introduction of the iron seems to be the chief change. This second variety is identical with 149 and 214, and is closely related to 224. The third variety is a crystalline hematite which is formed from the second by a complete ferration. The boundary line is irregular and vague, and the residuary patches of the second variety are quite as common, if not as conspicuous, in the hematite as those of the first are in the second.

The section contains varieties 1 and 2. The first variety shows clearly the spotted-granular structure, and indicates no mechanical disturbance. The granules are large, subangular, and are closely fitted together. They contain so little besides silica, however, that in the hand-specimen they are not distinguishable from the interstitial spaces. They are clouded by a thinly scattered dust. The silica is very finely cryptocrystal-

line, while that of the interstices is coarser, varying from cryptocrystalline to finely phenocrystalline. The change from 1 to 2 is marked by an impregnation of limonite, which replaces the silica. First the fine silica of the granules is replaced, and until this is entirely accomplished the interstices are not usually attacked, so that the granules become pellets of iron oxide with the crevices filled in by silica. Gradually, however, these bodies broaden, and eventually the interstices become much reduced in size, and sometimes disappear. It is evident that a complete replacement of the silica gives, if all the iron be in the yellow hydrated state, a soft ore like the yellow bands in the Mountain Iron mine. If the granules remain, as they are apt to do, in the hematitic state, while the interstices are replaced by hydrated peroxide, a somewhat granular brown ore will result. Crystallization in small finely disseminated masses through the rock as hematite, without attendant consolidation, gives the "blue" granular hematite. These different processes will take place in different zones of the rock, according to its porosity and mechanical weakness, these qualities determining the amount of oxidization which may take place within a given time. The third variety of the hand-specimen is not represented in the slide. It differs by a nearly complete replacement of the silica, and the crystallization of the earthy limonite into hard ore.

SPECIMEN 204. The structure of this piece of hard ore reminds one of that of the more highly ferrated parts of 232, just described. Evidently the same process has operated here and the results are the same. The rounded granules are yet distinguishable, by reason of the removal of the interstitial matter, leaving cavities which produce the porous structure of the rock. According to the degree to which enlargement of the original granules, as described for 232, has gone on, their outlines become less perfect; and frequently there has resulted a considerable diminution in the size of the intergranular space. The granules are of hard hematite, but the abundance of the empty interstitial spaces expose them to easy hydration. All through the rock the effects of this are seen in the scattered yellow powder, and, as stated, upon its periphery it passes gradually into the soft ore of which it is a residuary fragment.

Conclusion: A violent mechanical fracturing of the original rock at Mountain Iron has laid a considerable strip open to freely oxidizing forces. The evidence of this motion is clearly preserved in 97, which is so situated, at an eminence

above the general plane of action of surface waters, that it has not been greatly altered. The fracturing, however, had for a result on this rock the removal of most of its iron in solution. At the same time, the silica which remained became crystalline. The iron derived from this rock, together with the iron from all parts of the iron-bearing rock which came under the action of the surface waters, found its way into the lower parts of the fractured area, and was there deposited, being able, under these conditions, to replace the easily soluble cryptocrystalline silica. All the stages of this replacement are seen in 232. The final result was a hard, porous, somewhat hydrated sesquioxide. It is interesting to remember, however, that the white and almost totally non-ferruginous nature of the primary variety of 232 shows that at a period prior to its impregnation by iron, it had been leached and its iron carried away to form the first layers of the ore-deposit. The subsequent replacement of this leached rock by iron indicates a filling up of the basin by the growing thickness of the ore. The ore seems to have been hard and porous at first, judging from the hematite portion of 232 and from the residuary fragment 204, but freer oxidation soon operated to reduce it to a state of more or less complete hydration. The extreme of this process is in the yellow goethite, but nearly all of the soft ore contains more or less of combined water. Opposed to this further oxidation and hydration, was the change in certain regions by partial crystallization to a granular and friable ore, such as the "blue" hematite.

GROUP FROM THE VIRGINIA BASIN.

The members of this group are 10, 11, 12, and 13. They are selected from different places, to show the general nature of change in the rocks as the proximity to the great Virginia ore-basin increases. Specimens 10 and 11 are from the same pit, about 400 paces south of the northeast corner of section 4, T. 58-17, and so about a mile north of the great ore-bodies. Specimen 12 is from a pit on the Wyoming property, which is situated about half way between the locality before described, and the ore-bodies; and specimen 13 is from a hard portion of the ore at the Rouchleau mine, where there is a large and valuable deposit, and which is surrounded by many others of the valuable mines of the Virginia basin. Thus a series, beginning with the rock at some distance away, and ending with that directly associated with the ore, is obtained.

SECTION 10. Made up of silica and magnetite, which occupy more than 99 per cent. of the section. The magnetite is evenly distributed through the field, in the form of irregular, compact masses, large enough to be visible to the naked eye, which usually have distinct crystalline boundaries. There may be, instead of the bunches of intergrown crystals, an attenuated string, which may be reduced at times to single individuals. Bands of magnetite with less definite crystal form, or lacking it entirely, are contained in the granules, and serve to emphasize the existence of the fast-disappearing spotted-granular structure. Sometimes these bodies form an internal network in the granule; sometimes they are external, and outline its rounded form. Besides this compact magnetite, the same mineral in the form of dust is distributed throughout the section. It is usually more closely massed in the granules, where it fills out the form suggested by the firmer skeleton. In other parts of the section this definite arrangement becomes lost, and the dust-like magnetite is scattered irregularly. The silica is of two distinct varieties. The first is that which has been denominated finely cryptocrystalline, and occupies the granules; the second is finely phenocrystalline, and is found in the interstices. Between the two there is every stage of gradation, and yet they are quite distinct, both in their position and their nature. It is a constantly observed phenomenon that when a mass of magnetite is bounded on one side by the cryptocrystalline silica, and on the other by the phenocrystalline, the first side is apt to have a rounded or irregular outline, while the second will be usually perfectly crystalline. This constant association suggests that the two kinds of silica may have the same relation as the two kinds of magnetite, that the finely divided sort passes into the coarser by a simple process of crystallization. Indeed, in many of the granules this change seems to be even now taking place, for not only does the coarser silica surround them and occupy the crevices in them, but along these fissures and sometimes far into the granule, the crystallizing motive appears to be at work. This process appears to be contemporaneous with the concentration of the magnetite dust into crystalline form.

The coarser silica is usually marked by a mechanical crack which runs through the middle of the area. There are often ramifying cracks extending from the main one, and these are sometimes extended so as to form a rude network. The main crack generally runs around the edge of the quartz grains, but

sometimes cuts through them. These are not found in the finer silica; and they were probably formed *after* the crystallization took place. If any strain were brought to bear on this rock (such any change of chemical relations or even of temperature, bringing about expansion or contraction), it might be relieved in the finely divided silica by the slipping of particle on particle, but in the more brittle and tenacious fragments of the coarser crystalline silica could only result in fracturing. These cracks are often seen to cut across a grain, forming two portions that extinguish nearly enough together to show that they were originally one, and yet at a slightly different angle. Cases of this can be observed where the angle increases, owing to more complete separation of the parts, till finally the original unity of the fragments can not be established. This suggests that the grains of the coarser silica may have been originally much larger than at present, and that the present individualized condition may have resulted in part from fracturing and re-arrangement. But the perfect transitions from the coarser to the finer sort show that while this process has undoubtedly had some effect, yet the crystallizing motive has been far more active. (See Plate VIII, Fig. 2.)

SECTION 11, from the same pit as section 10, in a general way resembles it. The chief constituents are again silica and magnetite; but while in section 10 magnetite formed from 25 per cent. to 30 per cent. of the field, in section 11 it forms only from 5 per cent. to 10 per cent. The remaining space, which in 10 is filled with magnetite, is in 11 occupied by open pores, which in general correspond to the shape of the magnetite masses, and from which it is evident that the iron has been dissolved. All stages of this dissolution can be seen, from the magnetite mass with an irregular gap on one side, to the cavity with fragments of magnetite still clinging to the sides, and finally to that with the quite clean siliceous walls. The line between the magnetite and the cavity is sharp, and there is no evidence of any alteration into other forms of iron previous to being taken into solution. The silica is exactly as described for 10, and the different varieties chiefly distinguish the granules, whose existence is still clearly seen. The magnetite dust which is associated with the cryptocrystalline silica does not seem to have dissolved out, but it has undergone a concentration into bunches. That only the crystalline magnetite has been attacked was probably due to the fact that it was more easily accessible to atmospheric influences, as indicated by its association and the

probable manner of its formation. The repository of a part of this dissolved iron is seen in the section to be two small veins, which are remote from one another, but if produced would intersect at an angle of about 120 degrees. At right angles to one of these veins there is a third and smaller one. They consist of persistent, but irregular bands of crystalline magnetite, which appear to follow mechanical fractures in the rock. In places the magnetite of these veins is riddled by irregular cavities, and along these and along the edges there is an evident decomposition to earthy hematite and limonite, so that often a mass of the yellow and red ores are seen surrounding a small residual core of magnetite. Often the whole of the magnetite band is cut by ramifying lines of hematite, which in places grow broader till they nearly coalesce. In the hand-specimen broader bands of magnetite are seen, but marked by the same features as these little veins: the sum of all of these veins contains enough iron to account for all the grains dissolved from the body of the rock.

SECTION 12. Composed of about 90 per cent. silica, about 10 per cent. of blood-red earthy hematite. About 80 per cent. of silica is phenocrystalline, showing brilliant polarization colors. The grains are of about the same size as the largest central ones of section 11. But the cracks which were noted as partly separating the grains, have here become larger, and contain earthy red hematite, deposited from iron-bearing waters which have forced their way in. The widening of these cracks and the consequent loosening of the mass has then been accomplished in two ways—first, by the partial solution and replacement of the silica by iron, and second, by the mechanical pressure exerted by the growing vein. The result is that the rock is extremely friable, and crumbles easily. The grains, however, still retain their interlocking forms, which show their crystallization in place. Considerable areas of these fragments extinguish nearly simultaneously or with a slightly undulating extinction. These areas seem to have been at first united, and to have been subsequently fractured. The cryptocrystalline silica occurs but in one place, where it forms a residual (?) fragment of considerable size.

The iron which in 10 and 11 accompanied this variety of silica is present also in this slide, but here it is entirely earthy hematite instead of magnetite, and is either scattered through the mass or arranged in more or less rudely parallel fibrous bodies. The iron leached from the rock since it was in the condition of

section 11 is seen in the hand-specimen to have been concentrated into a broad band, which consists partly of iron, in a highly oxidized and hydrated state, and partly of the silica which has not yet been replaced. It will be remembered that a part of it is also found in the crevices between the silica grains.

In outward appearance, and even at the first glance under the microscope, this rock resembles a loose, friable detrital sandstone. Both its structure, as explained, and its evident derivation and method of formation, show that this is not the case, but that it is one of the multitudinous peculiar phases of the iron-bearing rock. There is no trace of any original detrital grains, nor is the appearance of the silica like that of the clastic rocks.

SECTION 13. Dense opaque brown hematite. The ore is porous, being filled with irregular cavities, which occupy about 10 per cent. of the section. The walls of these cavities are lined with minute clusters of radiating dark red crystals, which, when detached, form asterisk-like bodies. Occasionally, in the ore, there is a little micaceous hematite. The resemblance of this rock, a residuary fragment of hard hematite in the soft ore of the Rouchleau mine, to specimen 204, the residuary fragment in the Mountain Iron mine, is significant. They are nearly identical, both in their composition and their porous structure.

Conclusion: There is a progressive change in the nature of the rock as one goes from the rim of the Virginia basin towards the centre. The first rock described is one which we know from our comparative study to be a phase already far advanced in the processes of metasomatism. The spotted-granular structure is still well preserved and the granules are marked by the characteristic finer silica, and by the presence of a part of the iron in the rock. Most of the iron, however, has been dissolved out of the granules and has crystallized either in the granules or the interstices, or partly in both, as it happens. Together with this re-crystallization of the iron, there is a corresponding process going on in the silica, by which the fine cryptocrystalline sort is seen to be passing slowly into the coarser phenocrystalline variety.

In the next stage, the iron which has been concentrated into disseminated crystals has been again dissolved and redeposited in impregnation bands along fractures in the rock. These fractures may run in any direction, but there is a general parallelism between the most conspicuous of them.

In the next stage we do not find these hard concentrated bands; for, with the increasing decomposition, they have apparently been again dissolved and carried still further on, till in the end they go to swell the ore deposits at the bottom of the basin. But the pulverulent oxide, which in the former stage had not been attacked, has in this been dissolved and concentrated into a band whose highly oxidized and hydrated character affords sufficient evidence of the conditions under which it has been formed. Here, again, the crystallization of the silica, noted as beginning in the first stages, has gone on till nearly all the rock is of crystalline quartz, in grains of somewhat uniform size. In the crevices between these grains iron oxide has entered, and has operated to separate the grains of silica, so that the rock is loose and friable.

In the last stage, a porous hard hematite is encountered, whose origin is evidently the same as the hard concentration bands in the other stages; and whose porous nature is probably connected with the spotted-granular structure of the original rock, as explained for the similar sort of ore at Mountain Iron. This hard ore is found as a residuary fragment in the midst of the soft ore, and doubtless the latter has been derived from it by the easy oxidation and hydration which the porous structure offers.

CHAPTER V.

CLASSIFICATION OF THE IRON-BEARING ROCKS, AND STUDY OF ADDITIONAL SECTIONS.

From the specimens which have already been described, and which cover practically the whole field of the different phases of the iron-bearing rock, we have ample material to construct a classification. In the course of the comparative study, the rocks have grouped themselves naturally in certain combinations, and these larger groups have been seen to owe their primary distinction to the effect of different agencies which have acted on them since their departure from the evident single primary type. Foremost among these groups is that characterized by the prominent spotted-granular structure. All the processes of change in these rocks have gone on very slowly, and in such a way that the working agencies must have been an extremely scant access of oxygen and carbonic acid, with perhaps some sulphuric and vegetable acids,—but these, it must be reiterated, in small quantities. From these agencies a gradual process of chemical alteration has gone on, so that the mineral composition of the rock entirely changes while the original structure is not greatly altered. This process of metasomatism may be called the *Normal Process*, since it has affected every part of the iron-bearing rock, is in perhaps the larger part of the rock unmodified by any other important process, and since most of the other processes are resultant and directly dependent upon its action. It starts with a rock which is plainly unstable even under very feeble atmospheric influences, and by slow and tedious stages finally arrives at combinations which are almost entirely stable under those conditions.

The first modification of this process has a somewhat catastrophic cause. The nature of this will be briefly considered later, but it results in the freer access of all the agents of atmos-

pheric decay. The gradual and slow normal process is thus rudely interrupted, and the rocks, in whatever stage they may happen to be, are rapidly decomposed and hurried into more stable forms. The rapidity of this change naturally produces somewhat different phases from those of the normal process, and the resulting rocks have in general a marked difference. This modification of the normal process may be called the *Oxidation and Concentration Process*.

Although the catastrophe which brought on the oxidation and concentration process may have been in the nature of some movement in the rocks, yet the phases formed by this process have not been directly greatly affected by this movement, but mainly indirectly, through the increased amount of altering agents to which the change of conditions gave entrance. The rocks of the second modification of the normal line, however, are those which owe their peculiar features directly to a motion of the rocks, which in general has brought about the obliteration of the spotted-granular structure, the intimate mingling of the constituents of the rock, and the development of a schistose or slaty structure. Rocks of this type may be said to have been operated on by the *Shearing Process*. As in the oxidation and concentration process, the shearing process may interfere with the normal process, at any one of its stages, since the catastrophe of which it is the direct result may occur at any time; and the phases resulting from its action differ somewhat, according to the degree of change which the rock has previously undergone under the normal process.

The third modification of the normal process consists in infiltration into the rocks of minerals which are probably derived from sources outside of the iron-bearing member, notably calcite and sometimes pyrite. This may be called the *Impregnation Process*.

The impregnation process may directly modify the normal process, or it may very often alter the effects of the shearing process. When it modifies the normal type alone, it generally attacks those phases of it which have become porous, or which have been strained in some way and so opened to freely percolating waters. It is thus seen to follow conditions the extension of which would bring on the oxidation and concentration process, and, indeed, it is in some cases an attendant and auxiliary to this process. From the nature of the shearing process, it will be seen that the rock is ordinarily left open to freely percolating waters, and thus the impregnation process has operated very often upon the schistose and slaty phases.

Under the Normal Line, we may make a subdivision into (1), the primary spotted-granular rocks; (2) the ferruginous spotted-granular rocks, and (3), the siliceous spotted-granular rocks. The first is marked by the predominance of the chloritic substance in the granules; the second by the predominance of iron, in the form of oxides or carbonate, and the third by the predominance of silica, in the same bodies. In all three the substance of the interstices is mainly silica. These subdivisions pass into one another very gradually, and the gradual process of transition thus outlined reaches from the little-altered rock where the grains of the green mineral are mainly angular or irregular, and closely crowded together, to the extremely siliceous phases where the last trace of the spotted-granular structure disappears, and the rock passes into a chert or jasper.

In the rocks which come under the oxidation and concentration class the most striking feature attending the complete decomposition of the rock is the separation of the iron from the siliceous components. Their difference in solubility makes this inevitable when the rock becomes porous and decomposed, and the result is that portions lying in the higher parts of a drainage basin will become much poorer in iron than originally, while those portions which are situated near the bottom of the basin will become much richer. Not only does this areal distinction hold, but in different bands of the same rock, even of the same hand-specimen, the same result is seen, here marking the stages of separation which finally go to make up the areal distinction. Thus the rocks of this type may be conveniently divided into, (1), the leached rocks, and (2) the ferrated rocks.

Finally, we may divide the phases arising directly from the shearing process into groups, according to their mineral constitution: (1), the magnetite-hematite slates (2), the chlorite-actinolite slates, and (3), the silica slates. In each of these subdivisions, the minerals which give the name predominate over all others. Much of this peculiarity of mineral composition may be supposed to have been given the rocks subsequent to the actual shearing, and to be due to rearrangement of the constituents; but on the other hand, each division of the sheared class may directly result from the shearing of a rock of the normal type, whose mineral constitution was analogous to its own. Thus the chlorite actinolite slates are chiefly derived by the formation of new mineral combinations, from the ferruginous spotted-granular rocks; the magnetite-hematite slates

are directly derived from the ferruginous spotted-granular rocks, but also by subsequent ferration, from either of the other sub-divisions of the normal types; while the silica slates are derived only from the siliceous spotted-granular rocks.

Under each of the principal divisions will be placed certain of the sections described above; and others which show important phases, but do not come in any of the groups which have been written about, will be described in their proper places at the same time. After a full description of these rocks has been given, a more detailed consideration of the processes and causes of the processes will be fully understood.

I.

THE NORMAL CLASS.

A. THE PRIMARY SPOTTED-GRANULAR ROCKS.

SECTION 53-1. Described on p. 68.

SECTION 39. Described on p. 67.

SECTION 14. In hand-specimen, massive; color dark green; texture finely granular; fracture conchoidal. Scattering crystals of magnetite may be just perceived with the naked eye. Three bands of the same mineral traverse the rock, of which two are very near together, and sometimes join. These two are about $\frac{1}{4}$ -inch wide, while the third varies from $\frac{1}{4}$ to $\frac{1}{8}$ of an inch. Along the edges of these bands is a weathered selvage strip, which is ordinarily distinguished by its rusty red color, and often by a thin seam of siderite, whose crystals are barely visible to the naked eye. These bands evidently follow pre-existing cracks. A layer of siderite has also been deposited upon a joint-surface.

Under the microscope the section is found to contain, besides the green rock, one of the magnetite bands. In the green part, there are two distinct structures, greenish granules, and transparent interstitial substance. The main part of the granules is made up of the chloritic substance, which is sometimes dark green, but very often rendered brown and opaque by the separation of iron oxides attendant upon its decomposition. In this substance are embedded well-formed crystals of magnetite. Around the granule there is a deep border of actinolite. The crystals are very small, especially within the border, where they are too minute to give brilliant polarization colors. They

are bunched in sheaves which are closely interlocked, with a tendency to lie at right angles to one another, thus giving a curious interwoven appearance. On the extreme outer edge of the border, where the crystals have opportunity to grow outward into the interstices, they are five to eight times as large as those within. The base of the sheaves is always at the wall of the granule, and from this the prisms radiate outward, so that when the intervening space is narrow the growths from the opposite walls meet and interlock in the middle.

The interstitial material occupies the spaces between the granules and it also cuts into them at times, or even occurs in spots which are quite surrounded by the materials of the granule. This intergranular matter, or ground-mass, is made up of small transparent interlocking grains, which in certain parts of the section are almost entirely of siderite. This mineral is distinguished by its low single refraction, its brilliant white polarization color, and by the rhombohedral cleavage which can sometimes be made out on the edge of the section, as a carbonate; and chemical tests show it to be the carbonate of iron. In other parts of the section the place of the siderite is taken by small grains of crystalline quartz. The change seems to be a replacement of the carbonate by silica. Both siderite and quartz include the crystals of actinolite. That the siderite in each of these spaces has lately undergone some disturbance, and that the grains may formerly have been larger than now, is indicated by the wavy extinction which usually characterizes them, for although each grain is distinct, yet the angle of extinction between contiguous grains is often very small. When this angle is very minute, there is often no mechanical disturbance to be noted in a crystal of actinolite which traverses both of them, but there is generally a difference between the angles of extinction of the parts of the actinolite which lie in the different grains, corresponding to that of the grains themselves. When the angle of extinction between the siderite fragments is larger, the actinolite is bent at the contact of the two, or is even broken, and the parts separated by a slight space. In other cases the separating space becomes larger, and the fragment is bent at a large angle to the stump of the crystal. Finally, fragments of which the original position can not be made out are included in the interstitial material. These sometimes have a curved outline, showing bending by the same force which produced the cracking of the interstitial material. This fracturing may be ascribed

to the same cause as that which is supposed to have produced the fracturing of the interstitial silica of sections 11 and 12. According to this, the period must have been immediately subsequent to the formation of the large grains of interstitial matter, for slight strains such as produced this are never absent from rocks, and may be due to any one of a great variety of mechanical and chemical causes.

The band of magnetite in the section is, on the whole, well crystallized. It incloses cavities of irregular shape, but crystalline outline, which are filled by siderite. On each side of the band appears the selvage strip of the hand-specimen, varying from one-fifth to one-tenth of the width of the band. Here the magnetite is scattered, sometimes in solitary crystals, but more often in attenuated bodies, which are rudely parallel to the band and alternate with siderite. These layers must indicate minor lines of weakness, which were formed at the same time as the crack which produced the larger band. The reddish color of this strip is due to the presence of earthy hematite. Generally the hematite bodies contain residuary cores of magnetite, and there is no evidence that any of it was deposited primarily in its present form. The siderite which is associated with it, here for the first time takes on crystalline form, and both this and the cleavage are well-marked.

Conclusions: There is no evidence of the existence of siderite in the rock prior to the magnetite. In the bands, it occupies cavities the walls of which are crystalline magnetite. In the body of the rock it surrounds the magnetite and every other constituent except the hematite. If heat has been the cause of the crystallization of the magnetite, it probably took place before the formation of the siderite; otherwise the latter would probably have been reduced to the oxide.

Two analysis of No. 14 were made by Mr. Alonzo D. Meeds, of the State University, with the following results:

FIRST ANALYSIS OF NO. 14 (CHEMICAL SERIES NO. 244).

Silica.....	SiO ₂	64.04	per cent.
Alumina.....	Al ₂ O ₃	2.11	" "
Sesquioxide of iron	Fe ₂ O ₃	2.81	" "
Protoxide of iron.....	FeO	22.14	" "
Lime.....	CaO	.60	" "
Magnesia.....	MgO	4.04	" "
Soda.....	Na ₂ O	.30	" "
Potash.....	K ₂ O	.11	" "
Water	H ₂ O	3.73	" "
Loss on ignition.....		.67	" "
Total.....		100.55	

SECOND ANALYSIS OF SAME SPECIMEN.

Silica.....	SiO ₂	58.94	per cent.
Alumina.....	Al ₂ O ₃	2.72	" "
Sesquioxide of iron.....	Fe ₂ O ₃	3.01	" "
Protoxide of iron.....	FeO	22.94	" "
Lime.....	CaO	.71	" "
Magnesia.....	MgO	4.74	" "
Potash.....	K ₂ O	.09	" "
Soda.....	Na ₂ O	.24	" "
Water.....	H ₂ O	3.35	" "
Carbon dioxide.....	CO ₂	3.72	" "
Total.....		100.46	

The very important results arising from these analyses will be seen further on, in the consideration of the nature of the original rock whence all the phases were derived. But it may be remarked that the first analysis differs from the second chiefly in that it has no carbonate present, while the second shows its presence in some quantity. From this it may be inferred that in the part which was first analyzed the replacement of siderite in the ground-mass by silica had been entirely completed, while in the second it was still going on.

SECTION 131. Described on page 52.

SECTION 185-A. The hand-specimen shows two distinct parts. The first is massive, without any cleavage, jointing, or other parting; hard; fracture irregular; color light gray on fresh surfaces, yellowing on oxidizing. This rock is thickly mottled with small grains of magnetite. The light gray, nearly white material between these particles is silica, the finely crystalline state of which gives a frosty look and a granular feel to the specimen. These grains seem to be firmly bound together, yet their cohesion is really so slight that it is difficult to make a good section. The second part is dark gray, banded, and heavy with iron. The banding is marked by lighter and darker shades; and there is a parting parallel to the banding.

Under the microscope, the massive part is seen to contain crystals of magnetite, surrounded by actinolite crystals, and imbedded in a ground-mass of finely divided crystalline quartz. The magnetite is distributed as in 14.

SECTION 185-B, does not belong to this series* but will be described here, to bring out its relation to 185-A. In this the banded part of the rock is represented. The lighter bands are made up of a felty ground-mass of finely crystallized actinolite, mingled with silica, through which are scattered small irregu-

*185-B should be classed among the phases formed by the shearing process.

lar fragments of magnetite. The magnetite is not crystalline, the fragments are much smaller than in 185-A, and they make up a much smaller proportion of the section. There is a slight tendency to a linear arrangement of the materials.

In the darker bands the linear arrangement is very marked, and the iron oxide (which is always magnetite) becomes more plentiful, so that at times the strips thicken till they join, and form a band of solid magnetite.

Conclusions: A rock related to 14, but with a ground-mass consisting entirely of silica, has been subjected to strain. The light bands are the zones of little motion, the dark ones of greatest movement, while in 185-A there was no shearing whatever. In both of the two classes of sheared zones, both the magnetite and the silica were more or less finely ground. Subsequently the iron was leached out from the light bands and became concentrated in the weaker zones. The lighter band is darker in the hand-specimen than in 185-A, notwithstanding the fact that it contains less iron. The darker color seems to be due to the finer division and distribution of the opaque materials.

SECTION 17. In the hand-specimen a dark grayish-green. On close inspection with the naked eye, there can be seen irregular dark bodies thickly crowded in a light green ground-mass. With the hand-lens, the interstitial matter appears to be finely crystalline quartz, while the rounded bodies appear aphanitic, with uniform color and conchoidal fracture. There are also small crystals, sometimes thickly scattered through the rock, which appear to be magnetite. There is in the rock no cleavage; it is medium hard, fracture conchoidal to irregular.

Under the microscope, the section is found to be made up of crystalline quartz, hematite, magnetite, calcite, and siderite. The whole structure is evidently derived from that of section 14, by a somewhat more complete silicification, and a further decomposition of the remaining original constituents, thus forming additional hematite, calcite, and siderite. The granules consist mainly of red and earthy hematite. They are irregular in shape and usually contain kernels of residuary magnetite. Sometimes the change has been quite uniform on all parts of the periphery, in which case a comparatively large kernel of magnetite remains in the middle. Often it has proceeded along reticulated cracks, in which event the residuary magnetite has been separated into a number of small fragments, scattered through the mass. The smaller the original body the more

complete, naturally, has been its oxidation. In a band about $\frac{1}{2}$ -inch long and $\frac{1}{4}$ -inch wide, magnetite still forms about 75 per cent. of the mass, while the hematite, encroaching on the periphery and traversing it in every direction, forms the remainder. The siderite has been mainly replaced by silica. Part of it, however, appears to have oxidized in places, and part still remains. In sheltered places, as where surrounded by magnetite or a thick growth of actinolite, the interstitial siderite still remains, enclosing perfect prisms of actinolite, as described in section 14. The oxidation of the green chloritic substance has produced semi-translucent, yellow bodies. In these bodies the concentration of the sub-microscopic dust of hydrated iron oxide has gone on, producing spheroidal bunches, irregular aggregations. Very often there has formed around the edges of the mass a thick rim of hematite, enclosing the remains of the green substance, and its decomposition products actinolite, siderite, scattered hematite and calcite, and free silica. It often happens that this interior mass becomes finally almost wholly of cryptocrystalline silica, either through the decomposition in situ of the original materials, or by the replacement of them by silica from extraneous sources. It is certain that the former has largely operated, and doubtless the latter has also been important in this case.

In the granules a ringed structure has been developed in three ways: 1. Often the scattered hematite in the interior of the granules tends to arrange itself in lines which are rudely parallel to the periphery, thus suggesting lines of weakness corresponding to the bounding surface. They are irregular, disconnected, and broken, and can in no wise be accounted for by concretionary action. They may be explained in this way: The oxidation of the original green substance or of the semi-decomposed carbonated mass brought on a shrinkage of volume. This contractile tension resulted in the development of lines of weakness, parallel to the periphery, and forming successively one within the other. Thus the most pronounced line, which would also be the first, would be that next the periphery; and as the contracting volume diminished, the lines of weakness developed might become so small that they could not be detected, or they might not exist at all. So we find that these rough concentric rings grow fainter and disappear as they approach the centre of the granule. These lines of weakness being also the lines of greatest oxidation, the separation of the iron oxide would go on faster along them, and thus they would soon be marked by a narrow zone of this material.

2. A granule contains a central residual core of magnetite, which is all that remains from the original body, the outer parts of which have decomposed to form siderite. A change of conditions has brought freer oxidizing agents, and as a result the siderite has decomposed along its edges to hematite or limonite. So there results a structure of three distinct concentric bands: the peripheral layer of dense red hematite; the rim of little altered siderite; and, finally, the inner kernel of magnetite. If all the magnetite has been carbonated, the structure will consist only of a rim of hematite surrounding a body of siderite.

3. Rarer and less important, a certain banded structure has been produced in a third way. A mass of the original greenish material, (which, however, is often mainly decomposed to a confused mat of actinolite, magnetite, silica, and the carbonates), has been separated from the next granule, of the same or a slightly different variety, by a long and narrow band of interstitial siderite. The reduction of this siderite to the oxide gives a succession of layers, often curving, which may be composed successively of magnetite, hematite, actinolite, hematite, actinolite, (hematite), magnetite, and so on, the variety in the exact succession of the layers being great, since it depends upon the stage of alteration of the granules.

Oftener, however, the stages of change, instead of producing concentric rings, have for effect a fantastic marking of the granules. Thus, in the first process described, the decomposition of the green original substance gives rise to the clustering of ferruginous matter in spherules and irregular forms, around which there is usually a ring of cryptocrystalline silica. In this section the last operation has been the almost complete separation of silica and iron oxide in places. All stages of all the processes described may be seen in the section.

The interstitial silica is made up of small grains of crystalline quartz, somewhat uniform in size. The interstices and fissures have become more numerous than in section 14, and so divide the rock that the spotted fragmental appearance is apparent to the naked eye. These additional fissures were developed subsequently to the introduction of the carbonate; and must have attended the introduction of the interstitial silica which fills them. They may have resulted from the reduction in volume attendant on the decomposition of the green chloritic substance and the reduction of the siderite to the oxide, or by the wedging exerted in incipient fractures by the crystallizing

silica; the cause of the fractures, in turn, being probably due to strains generated by the changes of volume attendant upon the decomposition of the various minerals. Without doubt both of these causes have operated. Subsequent to the opening of the fissures, decomposition of the granules along their walls have served to continually widen them, and at the same time to make the granules themselves smaller, and reduce their angular shapes to well rounded forms.

SECTION 125.—In the hand-specimen, it is green in color; fracture irregular to conchoidal; mottling of lighter and darker green observable, but not highly conspicuous. Small grains of carbonate are scattered through the rock, and rarer crystals of iron pyrite. Under the microscope, there is a distinct spotted-granular structure. The granules are mainly composed of the green chloritic substance, sometimes quite fresh, but oftener decomposing to form silica and the iron oxides, showing perfectly every stage of the change as described in section 217. The engranular silica resulting from this decomposition is much finer than that of the interstices, but when the process of change is far advanced the two grades of silica sometimes become confounded, especially along the edges, so that the outlines of the granules become indistinct and sometimes indistinguishable. Imbedded in the chloritic substance are crystals of siderite, individual or twinned, of sufficient size to be visible to the naked eye. This is evidently the last mineral which has formed in the slide. (See Plate VI, Figs. 1 and 2)

SECTION 83.—Described on page 81.

SECTION 217.—Described on page 84.

SECTION 128-B, *variety 4*. Described on page 49.

SECTION 130.—Described on page 52.

SECTION 129.—Described on page 51.

B. THE FERRUGINOUS SPOTTED-GRANULAR ROCKS.

SECTION 143.—In the hand-specimen, mottled red, white and black; fracture irregular; a rude horizontal parting. Under the microscope, the granules are seen to have been produced largely by concretionary action, in addition to the more usual causes. The ground-mass, or interstitial substance, ranges from finely cryptocrystalline, through coarsely cryptocrystalline to finely phenocrystalline silica; and the larger part of the granules are composed of the same material, but here the silica is usually finer-grained. (See Plate VII, Fig. 2.)

The granules here may be divided into four classes, according to their origin. Most of these classes have been described previously, in separate sections, but it is rare that they are all found in such a small space as in this slide: (1) The true fragments, somewhat corroded. These are ordinarily distinguished by the presence of a certain amount of residuary siderite in the centre of the granule, and by silica of different grain from that of the interstitial spaces. (2) The irregular ringed impregnations described under section 131. These are discerned by the substance inside the ring being nearly or quite identical with that outside. They are of small importance in this section. (3) The true concretions, distinguished by their rounded outlines, and the regularly alternating and persistent rings. These concretions generally combine with 1 or sometimes 2 to produce the final form, taking these for nuclei, around which a border of rings is formed. Sometimes, however, the whole granule is concretionary, the nucleus being a grain of silica, or a separated lump of iron oxide. (4) The pseudo-concretionary rings, as described under section 17. This is really a modification of 1. They have no truly concretionary cause, but are phenomena attendant upon the contraction of the sideritic granules under atmospheric influences and the oxidation of the carbonate into hematite or limonite along the concentric lines of weakness thus induced. Both 1 and 2 are surrounded by peripheral rings of iron oxide, which, although they resemble one another, have a quite different origin, those of 1 being due to the oxidation of siderite granules along their periphery, and those of 2 to the impregnation by iron from chalybeate waters which had found their way along lines of special weakness. The hematite, in bodies of whatever origin, shows a tendency to concentrate into spherules, without, however, interfering as yet with the original structure. This concentration is probably the first step preparatory to the crystallization of the iron.

SECTION 208.—In the hand-specimen dark gray and siliceous; slightly spotted. In places it is porous, especially in the neighborhood of a band of iron which runs through the rock. There is a clearly slicken-sided surface on one side of the specimen. Under the microscope the rock is seen to be well advanced in the normal process of change, and is approaching the crystalline "jasper" condition, under the influence of crystallizing forces. As yet, however, the granules are quite distinct. They are marked by a kind of silica which generally differs in grain from that of the interstitial spaces, although in

one case it may be finer and in another coarser than it. As a whole, this silica varies from finely cryptocrystalline to a common type composed of well crystallized grains of considerable size. Magnetite occurs frequently in the section, but is always restricted to the granules. It is in large irregular masses, in smaller slender straggling bodies, or in very small perfect crystals. A small amount of red earthy hematite is also found, with some limonite, and a quantity of cloudy siderite much greater than that of either of the oxides. These are all shown, from their distribution, to be decomposition products of the magnetite, which they surround, leaving the magnetite as a residuary kernel, and in some cases entirely replacing it. The predomination of the siderite shows that freely oxidizing agencies, which would have directly produced hematite and limonite, have not had free access to this rock, and this inference is supported by the crystallization of the silica. Were the oxidizing influence greater, the iron would all be dissolved out and precipitated elsewhere, and the silica, instead of crystallizing, would disintegrate into a light porous rock, which ultimately would become a silica powder. The iron band in the hand-specimen seems to mark an area of such oxidation, as is shown, not only by the concentration of the iron, but by the light and porous nature of the silica in its immediate vicinity.

SECTION 34. Composed almost entirely of silica, magnetite, and hematite. The granules are of magnetite and hematite, with cryptocrystalline silica, or of silica alone. The interstitial silica is much coarser. Magnetite is in ragged masses, generally; rarely a perfect crystal outline has been preserved. Hematite in all cases is a decomposition product of the magnetite. In this section are certain bodies which appear to be truly concretionary, together with others in which the ringed structure is without doubt the result of weathering action. The true concretions are composed of alternating rings of iron oxide and cryptocrystalline silica. The original state of this iron oxide, so far as it is exhibited in this section, is a magnetite, but it has very generally decomposed to hematite, in the narrower bands completely. As a result of this decomposition since the formation of the concretions, the rings are apt to be somewhat broken in places. They surround as a nucleus a mass of magnetite, one of the original granules, a core of cryptocrystalline silica, or an area of the interstitial silica. Those bodies which show a ringed structure, which appears to be due to weathering, have in the outer parts a dingy zone, without

evident banding, which contains small irregular fragments, apparently residual, of magnetite and hematite. Next is a zone rather richer in iron, with a faint banding, in which the lines are very close together. Next comes a zone where the bands appear as rifts in the iron oxide, which have been filled with silica; and finally the dense inner kernel of magnetite and hematite. It is probable that the iron derived from these decomposing masses may have gone to form the true concretions.

The magnetite in this section, even where it shows crystal form, is usually so distributed that its derivation from siderite is probable. For instance, a common position is as a peripheral ring around a granule, the interior of which is mainly made up of silica. The only satisfactory explanation of this is that this ring represents a decomposition border of hematite around a body of siderite; that the remainder of the siderite, subsequent to the oxidation of its periphery, was replaced by silica; and that the hematite became afterwards changed to magnetite. Moreover, the process as described has been fully observed and described in other sections. Yet, even in these peripheral rings, the magnetite has crystallized so that in some cases the rim is made up of a string of connected crystals. The amount of silica in the specimen from which this section was made, has been very kindly determined by Mr. R. B. Green, of Virginia, as 84.75 per cent.

SECTION 41-A. *Variety I*, described on page 62.

SECTION 21. The hand-specimen is hard, with a conchoidal fracture, a prevailing dark-gray color, and a noticeably high specific gravity. It is coarsely brecciated, showing angular fragments, several of which are over an inch in diameter and one nearly two inches. These large fragments are, in their freshest state, a dark-gray, nearly black, flinty chert; but often there is a red rim around them which is the result of the first stages of their oxidation. This red rim, in other fragments, extends inward till there is only a small residuary fragment of the gray chert left, and finally there are fragments which are wholly of the red material. Along with the change of color, there comes a decrease of the hardness, and the surface of fractures becomes rougher and more irregular. From these coarse fragments there is every possible gradation in size down to the finer fragments or granules which are scattered thickly through the rock. The smaller the fragment is, the more effectually has corrosion, which in the largest has had but little effect, destroyed the angular outlines; so that the

smallest have the rounded form which is most usually found among the granules of this rock. Between the larger fragments, and around them, are rims and interstitial fillings of crystalline vein-quartz, the crystals being large enough to be visible to the naked eye. These show that the process of brecciation has in this case been sudden. This is evidenced, not only by the production of fragments of large size, which never result from the usual interstitial movements in the rock; but also by the cavities which were left at the end of the brecciation, and which were subsequently filled by the vein-quartz. Under the hand lens iron pyrite is found to occur in sparing quantities.

Under the microscope the rock has the usual spotted-granular structure, except that many of the fragments are larger than in the typical occurrence. This may be ascribed to the catastrophic nature of the process in this case. In shape the granules are irregular,—rounded, subangular or (rarely) sharply angular in outline. The composition of the granules is chiefly hematite, with magnetite and silica, some small amount of siderite, and a very little actinolitic (?) matter. Magnetite occurs, rarely, with complete crystal form; but usually it is found residual in the midst of an irregular mass of hematite, in the shape of a ragged core, a straggling network, or as scattered grains. The hematite in no case has, however, assumed the crystal form of magnetite, but is in shape as irregular as those of the residual cores themselves. Often hematite is thickly scattered through a granule in little bunches, the remainder of the space being chiefly taken up by siderite, in small, rusty grains. Actinolite, in very small clusters and sheaf-like forms, is an unimportant but constant constituent of the granules. Epidote (?) as a decomposition product is sparingly present along the edges of the iron oxide masses.

From the noted relations of the three forms of iron, we may reason that the iron was originally, so far as this section is concerned, in the magnetic state; that from this the first change was to the carbonate, which, again, has been oxidized to hematite. In ordinary cases, the hematite appears to be a direct decomposition product of the magnetite, but it is very probable that there was an intermediate carbonate stage. In certain of the granules the following succession may be observed: The central grains of magnetite are surrounded by an irregular and somewhat clear zone, which is composed chiefly of siderite. On the outside of this zone hematite appears, and grows more im-

portant as the distance from the centre increases, the periphery of the granule being generally marked by the densest ring of opaque hematite. In some of the granules finely crystalline silica has replaced the siderite, and occupies its place. The granules are ordinarily traversed by fissures, which from their shape seem in most cases to be due rather to contraction than to breaking by outside forces. Often these are not connected with the intergranular spaces, in which case they follow a course roughly parallel to the periphery. In other cases, they extend from the periphery inward, being widest at the margin and gradually tapering. Sometimes these last are extended so as to divide the granule into two, as before noted. These fissures are always filled with finely crystalline silica, and, especially the ringed ones, seem to have been formed by the contraction attendant upon the oxidation of the siderite to hematite.

SECTION 151. Described on page 74.

SECTION 166. Described on page 59.

SECTION 20. The granules are composed of magnetite, of cryptocrystalline silica, and of the brown oxidized material which represents the original greenish chloritic substance. There is no trace of any carbonate in the rock. The interstitial silica is coarser, and often contains crystals of magnetite similar to those of the granules.

This escape of the magnetite from the granules and concentration in various parts of the rock has led to a certain distribution of it in three rough areal divisions: (1) a broad, irregular band, comprising about one-third of the section, in which the magnetite, though by no means consolidated, is most closely grouped. The crystal outlines are sometimes sharp, but in general they are rounded, and often they are absent entirely. (2) On one side of this band the rock is characterized by somewhat regularly distributed magnetite in masses, with clean crystal outlines. For a very narrow strip, however, which lies immediately next the darker band, there is a distinct paling of the rock, owing to the partial disappearance of the magnetite; and what still remains has rounded outlines. (3) On the other side of the darker band the strip which has been deprived of magnetite is very much wider, and, indeed all the rock on that side shows the effects of the process which has operated to dissolve its iron and concentrate it in area No. 1.

The central darker band appears to have been induced by a rough mechanical crack, which runs through its middle. The resulting concentration along this line of greatest oxidation is here seen in its earliest stages. It is evident from the leached appearance of band No. 3 that most of the iron which has gone to enrich area No. 1 has been derived from it, and, from the fresh and unaltered nature of the magnetite of No. 2, that it has contributed little or nothing to the darker band. So we may conclude that the controlling agent in the removal of the iron and its carriage to the area of concentration has been water acting under the influence of a single power and moving in a constant direction,—that is to say, acting under the influence of gravity,—and that band No. 3 was situated above the concentration area. In band No. 2, the very narrow strip lying next the concentration band must be accounted for by capillary attraction acting in opposition to the force of gravity. By this force the larger body of iron has been able to draw into coalescence with itself the more scattered iron for a limited distance from its lower side.

In the concentration area, there are about equal parts of iron and silica, which have no definite arrangement. From 5 per cent. to 10 per cent. of the magnetite has decomposed, to hematite or yellow-brown limonite, and this process has rounded the edges of the crystals. In the concentration area the spotted-granular structure is only faintly seen; but in the areas on both sides it is very plain. The silica of the concentration area is in the main of the finely divided cryptocrystalline variety, although it ranges from this through coarse cryptocrystalline to finely divided phenocrystalline; and in those parts of areas 2 and 3 which are nearest the concentration area the silica is finest, and gradually and uniformly grows coarser as the distance increases, and as the amount of iron which remains increases. This suggests that the fine is derived from the coarse under the influence of the same atmospheric agencies which have brought about the slight concentration of the iron.

SECTION 65. Hand-specimen colored dark-gray, spotted with red; prismatic jointing; no cleavage; fracture conchoidal. Under the microscope there is seen to be a spotted-granular structure. The granules are composed of silica, hematite, magnetite, and limonite, the relative abundance of the respective minerals being in the order named. A single granule may contain any one of these, to the exclusion of others, or all of them, in

any proportion. The silica of the granules varies from coarsely chalcedonic to very fine cryptocrystalline, and from this very gradually to a phase where no individualized grains can be seen with the highest magnifying power, and thus it remains dark under crossed nicols. So it may be styled *amorphous*, but the gradation observed suggests that it is only a phase of the cryptocrystalline silica where the grains are sub-microscopic. But we are here able to trace, in following the changes from this apparently amorphous phase to the coarsely chalcedonic, and from this to the finely phenocrystalline silica which predominates in the interstitial spaces, the stages of progress of the crystallizing action. Magnetite occurs sometimes in small, well-defined crystals, which are always directly surrounded by silica, in irregular central masses, or as rims to the granules, when it is always surrounded by a decomposition border of hematite and limonite. It is clear that the small crystals of magnetite are younger than the larger and more decomposed masses, and their secondary origin is further shown by their sometimes occurring in the ground-mass. The magnetite and hematite which is confined to the irregular masses in the granules, however, is probably derived from the decomposition of siderite granules. The remainder of the granule is usually composed of silica, more or less stained with iron oxide. A typical structure in these granules is the following: on the periphery, a rim of magnetite; within this a zone of cryptocrystalline silica; and, finally, a central mass of hematite, with some magnetite scattered in the center. This structure may be explained by supposing (1) that the fragments of magnetite in the center represent the product of the substance of which most of the granule was originally composed. (2) This magnetite was altered to siderite, a change which is seen going on in many sections. (3) The carbonate became oxidized on the edges to hematite. (4) Next, silica began to replace the siderite along its outer edges, within the peripheral rim of hematite. (5) The rim of hematite was changed to magnetite. This supposes that hematite may be converted to magnetite with greater ease than siderite, and that the siderite was not affected by the conditions of alteration, which were of a reducing nature, while the change from siderite to hematite or magnetite is best brought about by free access of oxidizing agents. (6) Before the replacement of the central siderite by silica had gone very far towards the core, a change of conditions and the recurrence of oxidizing agents had transformed the siderite into hematite, which was not easily replaced.

The prismatic jointing of the rock may be ascribed chiefly to the reduction of the carbonate to the oxide, which was also probably the cause of the rough, horizontal parting. Had the volume of the carbonate been greater, as in specimen 18, (see p. 131.) the contraction might have multiplied these horizontal joint-planes indefinitely, resulting in a sort of slaty cleavage.

An analysis of this specimen by C. F. Sidener, of the State University, gave the following results:

ANALYSIS OF SPECIMEN 65 (CHEMICAL SERIES NO. 237).

Silica.....	SiO ₂	85.97 per cent.
Alumina.....	Al ₂ O ₃	.67 " "
Sesquioxide of iron.....	Fe ₂ O ₃	11.40 " "
Protoxide of iron.....	FeO	.90 " "
Lime.....	CaO	.01 " "
Magnesia.....	MgO	.02 " "
Potash.....	K ₂ O	.01 " "
Soda.....	Na ₂ O	.01 " "
Water.....	H ₂ O	.30 " "
Total.....		99.29

SECTION 72, *Variety I*. Described on page 75.

SECTION 74. Described on page 77.

SECTION 82. Described on page 80. This shows such evident oxidation, and the results of this alteration in the entirely decomposed rock (No. 70) are so striking that it will also be listed among the rocks derived from the oxidation and concentration process.

SECTION 171, *Variety I*. Specimen 171 is in the hand-specimen a coarse breccia, like 185. Compare also specimen 21. The fragments are often two or three inches long, and are sharply angular, in general. That they have been but little moved from their original position in the rock, previous to the brecciation, is shown by the fact that neighboring fragments often correspond in shape, so that it is possible to see that they were once connected, and to recognize the line along which they were broken apart. In their freshest state the fragments are of a gray chert, often containing small crystals of clouded siderite. Frequently, however, oxidation has produced around the edges a band of bright red, which is sometimes a mere rim, but again has developed till there is only a small fragment of the gray left in the centre, and at times, when the fragment is small, has transformed the whole of the gray to the red. The ground-mass, which surrounds these fragments, is dark red, mottled with dark gray, and flecked with white spots of siderite, which are much smaller than the siderite crystals of the frag-

ments. The section made contains parts of three fragments, of which two are small and rounded, and the other large and angular.

Variety 1. The ground-mass. In structure this is spotted-granular; the granules are rounded or subangular, and are closely crowded together. They are distinguished from the intergranular spaces chiefly by the iron oxide which they contain, for, although their silica differs in some cases from that of the interstices, yet there is no fixed rule. Magnetite occurs as small crystals or as irregular fragments surrounded by a dense decomposition rim of hematite. This hematite is also scattered thinly, as a staining material, through the larger part of the granules. Siderite is in small, irregular, ragged masses.

The rest of the varieties of this section belong properly under the shearing process, and will there be listed, but in order to explain their relation to variety 1, they will be described here.

Variety 2. This is the outer rim of the larger fragment. It is a very narrow selvage border, about $\frac{1}{16}$ inch wide, composed of silica somewhat uniformly coarser than that of the ground-mass. This silica is clouded by iron oxide dust, the particles of which are arranged in a faint banding, parallel to the sides of the fragment. This seems to represent a zone of trituration against the ground-mass. Compare section 40.

Variety 3. The interior of the larger fragment. This structure is very clearly that of the ground-mass, variety 1. There has been, however, an elongation of the granules, parallel to the sides of the fragment; and in some cases the granule has been broken, or even shred, and the pieces scattered through the intergranular spaces. Attendant upon the movements indicated by this, there has been the disappearance of the siderite and most of the magnetite, which have become oxidized to earthy red hematite. This hematite pervades the granules, and gives the red color to the rock.

Variety 4. The two smaller fragments, which are each about a third of an inch in diameter. Here the traces of the spotted-granular structure have been obliterated, apparently by a continuance of the crushing action whose effects are noted in variety 3. As a result, there is a mingled mass of silica and iron oxide, with no definite arrangement. Sometimes one mineral prevails, sometimes another.

Conclusion: There is between the ground-mass and the fragments a likeness which shows them to be identical in origin. The brecciation and subsequent oxidation has not destroyed the likeness between the larger fragment and the ground-mass, but in the smaller pieces the original structures have become so confused that the rock comes to resemble the larger fragment much less than does the larger fragment the matrix. The order of profundity of change is 1, 3, 4, 2. Since in this case we find that the larger fragments have the same structure as the ground-mass, it must be that the exact period of the formation of these fragments was subsequent to the introduction of the spotted-granular structure. We may suppose that by small local movements successive slight strains were accumulated, till they grew to be important; and then by their sudden discharge, the shattering resulted. Before this accident, the rock was well advanced in metasomatic change, had developed small crystals of siderite, and was passing into a sideritic chert. Section 78 represents this type of rock.

SECTION 78. Described on page 78.

SECTION 33-A. Specimen 33 contains two distinct bands, of which the first is represented by 33-A, and the second by 33-B. There is in the hand-specimen no means of clearly determining the relation of these two parts. 33-A has to the naked eye the appearance of a chert, dark gray, with smooth conchoidal fracture; while 33-B has a distinct lamination, is lighter in color and softer, and contains small thickly crowded dark fragments in a light-green matrix. The specimen is from section 8, T. 58-17.

Under the microscope, 33-A is found to be made up chiefly of silica, with siderite, hematite, and magnetite, some clayey and chloritic matter, and a little pyrite. The spotted-granular structure is well preserved. The granules are marked by the presence of the iron minerals, which form peripheral rims, rude internal concentric rings, interlacing network, or scattered and irregular fragments; the remainder of the granule being occupied by silica. These structures are usually of siderite, but sometimes they are of hematite, and occasionally of magnetite. The magnetite never has crystal form, and is almost invariably surrounded by its decomposition products, hematite and siderite; very rarely it is in contact with the silica. Hematite is always a decomposition product, generally of magnetite, rarely of siderite. Siderite usually occurs surrounding a residual kernel of magnetite and hematite or of hematite alone.

When the original mass of magnetite has been small or narrow, it may have been completely carbonatized; and in this case the siderite is often beginning to assume crystal forms. The order of the formation of the iron ores in this slide is seen to be that which has been repeatedly noted elsewhere,—magnetite to hematite, hematite to siderite, and in rare cases, siderite to hematite again. But the manner of the formation of the magnetite rims to the granules, and the other forms in which the magnetite occurs in this section, has been sufficiently observed and described in other sections, as follows: An initial mass of siderite becomes oxidized around the edges into hematite or limonite, which then forms a dense peripheral rim. This decomposition may also have penetrated the siderite along cracks, to form a straggling network. The remaining siderite was then replaced by silica, and a change of conditions altered the hematite to magnetite. This state is the earliest which we have in the present section. Taking in this section, then, the rare instances where siderite which has been derived from hematite is beginning to oxidize along its borders to hematite again, we are quite certain that we can trace its ancestry as follows: Siderite, (the initial body) hematite, magnetite, hematite, siderite, hematite. But in some sections the initial body of siderite itself has been shown to have been derived from a yet earlier magnetite, with, in general, an intermediate hematite stage, and so it is quite probable that we may with accuracy in this case trace the ancestry yet further back, in this manner: magnetite, hematite, siderite, hematite, magnetite, hematite, siderite, hematite.

The silica of the interstices is finely cryptocrystalline; that of the granules appears at first amorphous, but under the highest magnifying power there can with difficulty be distinguished the individual grains.

SECTION 33-B belongs to the class of rocks formed from the normal phases by the shearing process, in combination with the impregnation process, and will there be listed; but will be described here, for the better understanding of its relation to 33-A. It is composed of dark, irregular bodies in a matrix of crystalline calcite (magnesite?) These bodies, which make up about 60 per cent. of the section, do not resemble the granules of 33-A. In size they are not uniform, and in shape they vary, being sometimes rounded, sometimes sharply angular in outline. Neighboring fragments are so shaped that they would match so as to form a single mass, were they applied, and of-

ten a large piece has been ripped and shred without being quite separated into distinct pieces. The material of these fragments is dark-green in color, and very fine-grained. They are always traversed by a set of regular darker parallel lines. When the fragments are little removed from one another the lamination of one is often nearly parallel to that of the other; but often there is a considerable angle, and in this case the angle between the neighboring and corresponding sides of the fragments is apt to be the exact complement of the angles made by the lamination. These facts go to show that these fragments have been but little removed by the brecciation from the place which the simple schistose rock from which they are derived, occupied.

These schistose fragments belong to the phase which is elsewhere represented by 27-A (variety 4,) 29, and others. It is composed of a fine mass of chlorite, hematite and magnetite in varying proportions, with siderite and calcite. The history of 33-B, then, is probably this: A fault or local shearing in the rock produced from 33-A, a schistose band. (The production of 27-A, variety 4, from 27-A, variety 1, is strictly analogous) The continuance of the shearing force finally crushed the already formed schist, and thus produced a breccia, the matrix of which was soon supplied by the infiltration of xenogenous calcite. In the hard specimen, a dense black layer overlies 33-B, which, it may be, is composed of still more highly comminuted fragments, and so was nearest the actual line of movement.

SECTION 27-A. *Variety 1.* Described on page 53.

SECTION 27-B. Described on page 56.

SECTION 27-A. *Variety 2.* Described on page 55.

SECTION 161-A. Described on page 57.

SECTION 128-A. Described on page 46.

In the last few sections which are listed, are found the immediate transition stages to the next subdivision.

C. THE SILICEOUS SPOTTED-GRANULAR ROCKS, CONCLUDING WITH THE CHERTS AND JASPER.

SECTION 37-B. Described on page 66.

SECTION 93. In the hand-specimen traversed by broad bands, with irregular borders. On one side there is a banded rock with a rough feel, which passes to a yellow-brown siliceous rock, and thence to a nearly black "jasper," in which small

grains of magnetite can be seen. The siliceous parts are flinty, with conchoidal fracture, and no cleavage or jointing. The section is cut from the black part.

Under the microscope there is no certain remnant of any spotted-granular structure. There is a ground-mass of very finely divided cryptocrystalline silica, in which are scattered small crystalline grains of magnetite, and still smaller bunches of confused hematitic-chloritic stuff. The magnetite shows no association with these smaller bunches, but has a tendency to arrange itself along certain microscopic cracks or lines of weakness in the rock. The banding thus produced is quite noticeable in the hand-specimen. Compare with this rock sections 40 and 41. (See pp. 61 and 62.)

SECTION 164. Described on page 58.

SECTION 210-A. The hand-specimen is from a pit 230 paces north of the east quarter-post of section 29, T. 58-20. It is a dark gray, flinty, subtranslucent chert, which is traversed by numerous cracks, the chief set of which are parallel to one another. Along these cracks decomposition has reduced the chert to a light colored, porous, and friable substance. Besides the chert, the other and larger part of the specimen is made up entirely of the decomposition product above referred to. The result is a light-brown rock, well banded, soft and somewhat friable, granular to the touch, and sometimes showing on a fresh surface small flecks of white in the brown. Section 210-A is cut from the pure chert.

210-A is seen under the microscope to be composed of nearly pure silica, which occurs as a uniformly and very finely divided cryptocrystalline variety, the individual grains of which are often so small that they can hardly be distinguished and so are very slightly removed from the so-called "amorphous" silica. The only other thing in the chert is a small quantity of almost invisible dust, which may be iron oxide. The section is traversed by the cracks described in the hand-specimen. Along these fissures there has been a very small impregnation of red iron oxide, which, in combination with the silica, has resulted in the production of some confused chloritic decomposition products. These impurities are exceedingly small in amount but they have operated to separate the grains of silica between which they form, and thus the light color, granular appearance, and friable structure of the rock is produced. This effect is first seen in the immediate vicinity of the crack, but as the process goes on there is a continued deeper penetration of the oxidizing agencies.

In this connection will be described section 210-B, although this really belongs under the oxidation and concentration class, and will be listed as such.

SECTION 210-B. This is cut from the light-brown portion of the rock, which has been formed by decomposition of the chert. There are lighter and darker bands, but they are not strongly marked. The darker bands contain more of the dust-like matter, the lighter parts very little. The rock is quite the same as the decomposed areas of section 210-A, except that in the darker bands the proportion of limonitic matter is somewhat greater. Along cracks these impurities have accumulated to a greater extent. There are also sparingly disseminated through the rock small rhombohedra of limonite, which appear to be pseudomorphs after siderite. These must have been in the original chert, although they are not seen in 210-A. They are of about the size of the usual crystals of carbonate in sideritic chert.

The cause of the cracks which initiate the changes in this rock may be (1) mechanical strain acting from an extraneous source; or (2) contraction resulting from internal causes, such as the removal in solution of some of the former materials, thereby bringing on a diminution of volume. From the smooth and regular planes which these cracks usually follow, however, and from the fact that they are arranged in several systems in which all the cracks are nearly parallel to one another, which systems intersect each other, it is probable that the first cause mentioned has had the chief effect, and the particular variety of this strain seems to have been torsion. But it is quite possible that in 210-B the tendency to weakness in what subsequently becomes the zones of banding may have first been developed by contraction.

SECTIONS 10 AND 11. Described on pages 93 and 94. Since in these sections the oxidation and concentration process has had a very important effect, and since they form the first members of one of the most instructive series of changes under this influence, they will be listed among the other representatives of it, as well as here.

SECTION 329 P. C. This has been very kindly loaned me by Mr. Peter Christianson, of the State University. It is in part almost a pure carbonate, in other places it is almost pure cryptocrystalline silica. This siliceous part is without doubt the least altered part of the rock, and the oldest in the section. It has the spotted-granular structure preserved with sufficient

distinctness, although it is marked only by the difference in grain of the silica of the granules from that of the interstitial spaces. All the iron has been dissolved out, and there is no trace of the original chloritic substance. In part of the section the ground-mass is almost of pure iron oxide, which has the appearance of having been a concentration area, and that here the iron derived from the solution of that in the granules of the siliceous spotted-granular portion has been precipitated, replacing the silica. Naturally, in this iron oxide area there remains no trace of any spotted-granular structure. Through the parts where the iron oxide is densest are scattered small perfect crystals of siderite, and these gradually increase in numbers till they occupy most of the space, and in one part there results a pure carbonate. Scattered crystals of the same sort are found in the silica, but sparingly. Whether found surrounded by iron oxide or by silica, they invariably have perfect crystal form, while the material which surrounds them never has, but has a distribution which shows great alteration. So there can be no question that the carbonate has been the last mineral to form in this section, and the gradual change from the scattered crystals of siderite in iron oxide to the extended areas of pure carbonate shows that even these last must be of the same age. From the association of the carbonate with the iron oxide, moreover, it must be that the carbonate has been directly derived from the oxide, through the action of carbonated waters.

Conclusion: A spotted-granular rock has been so far reduced by the processes of normal metasomatic change that it has approached the chert or jasper condition. The last of these processes which we may note in this section is the separation of the intimately mingled iron from the silica, and its concentration in a separate area. This process has been described before, and when completed there results the familiar banded silica and iron which is the characteristic so-called "jaspilite" of the iron regions. Subsequent to this preliminary concentration, the entrance of carbonic acid in solution into the rocks, in waters which passed through with extreme slowness, has brought about the gradual change of the oxide to the carbonate, which in some parts has gone on to completion. At the same time, what little iron oxide was left in the siliceous part of the rock was concentrated to form the disseminated crystals of siderite there. This carbonatizing process may

obviously take place at any stage in the history of the rock, and of the separation of the iron, when circumstances become favorable.

SECTION 35. Described on page 64.

SECTION 40. Described on page 61.

SECTION 97. Described on page 89.

II.

THE OXIDATION AND CONCENTRATION CLASS.

A. THE LEACHED ROCKS.

SECTIONS 11 AND 12. These form part of a series, which is described on pages 92 to 97, and are derived from section 10, described on page 93. Of these section 12 is really the only completely leached phase.

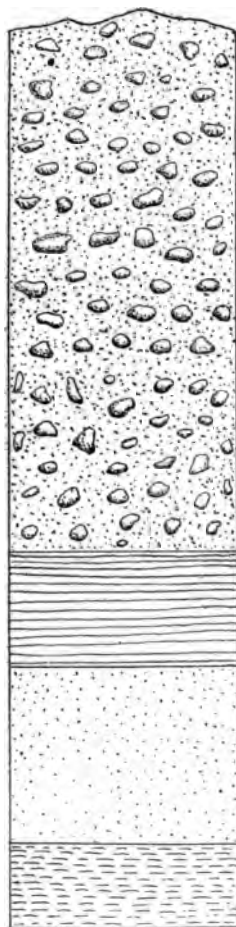
SECTION 19. In the hand-specimen it is generally soft and earthy, but still cohesive. In its most decomposed spots it has changed to a fine grey powder. There is in the centre of the specimen a large residuary core of hard gray, siliceous rock, which in places still shows the mottling due to the spotted-granular structure. The granules are seen to be darker than the intergranular spaces. It is from the decomposed brown part that the section is cut. In transmitted light it is nearly opaque, with the exception of very small irregular crevices which seem to be filled with finely divided silica. By incident light the substance is seen to be a fine white powder, irregularly and often deeply stained with hydrated iron oxide, and containing very small grains of crystalline silica. Conclusion: The formation of the brown decomposed rock from the central core of siliceous spotted-granular rock has been by a process of simple oxidation. Under this motive the silica has become very finely divided, so that the resulting fragments are submicroscopic. At the same time, most of the iron has been dissolved out, and the remainder of it transformed into excessively fine limonite, very thinly strewn. Although this iron has doubtless aided a great deal in forcing apart the individual grains of the original rock, yet this seems to be the natural process of decomposition of this variety of silica. This opacity is in part due to the presence of the iron, but the silica grains are so small that the section would probably still be opaque, even if no iron were present.

SECTIONS 70 AND 82. Described on pages 80 and 81.

SECTION 232. *Variety 1.* Described on page 90.

SPECIMEN 230. This specimen is from a pit near the Mesabi Chief mine, in the southwest of the southeast of the northwest quarter of section 23, T. 57-22. The record of the pit as given by Capt. Mallman is as follows: (See Fig. 9.)

Drift.....	31 feet.
Paintrock and lean ore.....	6 "
White, friable rock, crumbling to powder.....	11 "
Mixed ore.....	4 "
Clean ore.....	— "



Drift.

Paintrock and Lean Ore.

White Silica Powder.

Ore.

Figure 9.

Section of pit No. 1 in S. W. of
S. E. of N. W. sec. 23 T. 57-22.
Stopped on account of water.
(Courtesy of Capt. Mallman.)

Specimen 230 is from the "white, friable rock," mentioned above. When taken from the pit it was in irregular lumps, sufficiently hard to remain in shape, but porous and friable. On exposure to the air it speedily crumbled, on the slightest agitation, to a cream white powder, the individual grains of which could not be distinguished. The process by which the rock crumbled so quickly on exposure to the air was probably only an evaporation of the water which was in the rock at the time of being taken out, and which, existing as films between each minute grain and its neighbors, exerted enough capillary force to make a pretty firm cement. Analysis of the white powder shows it to be nearly pure silica. This analysis is given later. This powder has the same origin as the other rocks of this class which have been described, namely, the decomposition of a chert.

SECTION 36. Described on page 64. This belongs in part to this class.

B. THE FERRATED ROCKS.

SECTION 232. *Variety 2.* Described on page 90.

SPECIMEN 204. Described on page 91.

SECTION 138. Hand specimen soft and earthy; light red in color. Fracture conchoidal to slaty. Uniform in color, texture and general appearance. In places there is a slaty cleavage, and, more rarely, a prismatic jointing. The rock might be denominated in the field a "red slate." Under the microscope, it is earthy and nearly opaque. There seems to be a background of extremely fine silica, but this is stained and obscured by the finely disseminated iron oxides. By incident light these are seen to be mainly red and earthy—probably limonite—with scattered minute grains of magnetite. The section is quite uniform.

Conclusion: This rock differs from the ordinary decomposed cherts, such as specimen 70 (described on page 80), and other pulverulent rocks or powders which result from the same processes of weathering, only in being stained, and to a very slight degree consolidated by iron oxide. The history of the rock is therefore this: The original rock, after going through the whole length of the normal process, was finally reduced to the state of a chert or nearly pure siliceous rock. There may have been some slight amount of iron oxide left. This chert was, by some change, exposed to the more violent atmospheric forces, by which it was reduced to a fine powder.

Subsequently water bearing iron in solution filtered into this porous rock, and deposited a certain amount in the submicroscopical crevices between the grains of the powder, thus staining and to some extent consolidating it. This last process is the same as that which has formed the red and brown bands of specimen 70. The "paint rock" (See p. 128.) is also almost identical with this rock, but has in general been more deeply impregnated with iron.

SECTION 32. In the hand-specimen, yellow-brown and siliceous; resembles 19. There is a faint parallel parting or lamination, which at the centre of the specimen becomes curving, and follows the outlines of a large residuary fragment of hard gray siliceous rock. These lines thus represent the successive stages of decomposition, and the cause of their being thus marked may be the contraction of each successive shell as its chemical composition underwent the change forced upon it by the weathering process. And yet the lamination, as well as the decomposition, is by no means regular or constant, but the specimen is somewhat mottled by patches in various stages of change. Under the microscope the rock is seen to be mainly of silica, with some limonite. There is no constant structure; both minerals are very finely divided and are mingled together, without observable system. There are in the slide lighter and darker blotches, according to the predominance of one constituent mineral over the other. The process by which this rock has been formed from the coarser gray rock, of which the residual fragment consists, seems to have been a simple decomposition, without great change in the chemical composition, save, perhaps, for some addition of iron.

SECTION 13. Described on page 96.

SECTION 210-B. Described on page 73.

SECTION 150-A. *Variety 2.* Described on page 73.

SECTION 150-B. *Variety 2.* Described on page 73.

SECTION 149. *Variety 2.* Described on page 73.

SECTION 170. Hand-specimen quite soft; color brick-red; texture somewhat porous and granular, often friable, a well developed slaty cleavage. The surface is curiously pitted, and the pits resemble very closely rain-prints in shape. The section is made parallel to the cleavage, so the microscope shows no structural lines. The rock is made up mainly of silica, with iron oxide. There is no spotted-granular structure observable. The silica varies from finely to coarsely cryptocrystalline; the iron oxide is mainly magnetite, although this

is somewhat decomposed to hematite and limonite. Rarely, the magnetite has crystal form, but usually it has none; it has no definite arrangement, with regard to the silica, but it is scattered thickly in the ground-mass. This rock has the same genesis, in general, as 138, 70, and similar rocks,—a disintegrated siliceous rock, which has become, to some extent, impregnated with iron. It is from a pit in section 2, T. 58-18 (the northwest of the northwest quarter.) In the same pit are fragments of harder rocks. The blocks of this slaty rock have a beautiful prismatic jointing, which, in common with the cleavage is very certainly due to the shrinkage of volume attendant upon the weathering process and the loss of certain soluble constituents. The perfect development of both of these structures shows that the loss has been very considerable. The pits on the surface of one layer fit into corresponding elevations upon the next. The cause of these pits is found to be in numerous small residual fragments of the harder rock, whence this is derived. These are in most cases reduced in size to very small nodules, but the lines of cleavage which follow the decomposition, have run around them, as described in section 32, with the result that the otherwise plane surface of the cleavage has this pitted structure. This rock is found on the very border of a considerable ore body.

PAINTROCK. This name is given by the miners to a rock which is very closely allied to those which have just been described, but it has very little cohesion, and is generally more or less mixed with water, to form a stiff clay. The material of which specimen 70 is a sample, was at the surface mingled with water, and clay-like in nature; and, indeed, most of it contained water, which rendered it somewhat plastic until the action of the air evaporated the water and hardened the rock. This, then, might be called a white paint-rock, but the name is usually applied only to those forms which have been impregnated with iron oxide, subsequently to the complete decomposition. So we have red, yellow and brown paint-rock, corresponding to the red, yellow and brown bands of the rock from which specimen 70 is taken; and mingled with these are found frequent bands of the pure white. Sometimes the paint-rock becomes very rich in iron, and in places passes into ore. Besides the iron, the constituent minerals of the paint-rock are kaolin and very finely powdered silica, intimately mixed, the latter usually greatly predominating.

III.

THE SHEARING CLASS.

A. THE MAGNETITE-HEMATITE SLATES.

SECTION 29. Described on page 56.

SECTION 160. Described on page 56.

SECTION 161-B. Described on page 58.

SECTION 41-A. *Variety 2*. Described on page 63.

SECTION 72. *Variety 2* and *variety 3*. Described on page 63.

SECTION 128-C. *Variety 3*. Described on page 48.

SECTION 171. *Variety 2* (transition stage). Described on page 117.

SECTION 185-B. *Variety 2*. Described on page 105.

B. THE CHLORITE-ACTINOLITE SLATES.

SECTION 27-A. *Variety 3*. Described on page 55.

SECTION 128 C. *Variety 2*. Described on page 48.

The fragments in SECTION 33-B. Described on page 120.

C. THE SILICA SLATES.

SECTION 79. Described on page 79.

SECTION 127. In the hand-specimen, light and dark bands alternate, but certain irregularities in their course show that one has been derived from the other. Color gray; hard; fracture smooth-conchoidal. There is in the hand-specimen no trace of the spotted-granular structure.

Under the microscope, the light bands are seen to be composed chiefly of cryptocrystalline silica, and the carbonates, including calcite, with a small amount of iron oxide. The remnants of the granules which formerly characterized the structure still exist. They are composed of an aggregate of fine crystalline carbonate grains, containing irregular decomposed fragments of iron oxide, which may be residual. Carbonate is also distributed through the silica in a reticulating network, the separate links of each chain being made up of grains of carbonate. Sometimes these chains inclose silica

which differs decidedly in grain from that on the outside, and in this case they seem to represent the rims of former granules. In the cases where no difference is seen, these chains may still represent the granules, or, quite as probably, they may be simple impregnations of calcite in partings caused by the contraction of the chert. But from the association of 127 with specimen 123, a typical spotted-granular rock from the same pit, the derivation is quite certain.

The darker bands differ in composition from the light bands little or not at all. They differ in structure, in the obliteration of the traces of the spotted-granular structure and the reticulated chains of calcite; in the substitution of a somewhat finer division of the mineral grains, and a linear arrangement of them. Among these lines there has been some slight decomposition and also some slight concentration of the iron oxide, and these narrow zones, set very close together, have given the black color to the band. The contact between the light and the dark bands is not sharp.

Conclusion: The bands were developed from a spotted-granular rock through a shearing force, which produced the comminution of most of the materials, and opened it to the infiltrated calcite. Certain zones were more sheared than others. The result was a microscopic schistosity, and hence the dark color.

SECTION 185-B. *Variety 1.* Described on page 104.

SECTION 150-A. *Variety 1.* Described on page 73.

SECTION 150-B. *Variety 1.* Described on page 73.

SECTION 149. *Variety 1.* Described on page 72.

The last three sections listed are transition stages between the silica slates and the siliceous spotted-granular rocks.

IV.

THE IMPREGNATION CLASS.

SECTION 37-A. Described on page 65.

SECTION 219. Described on page 88.

V.

THE SHEARING-IMPREGNATION CLASS.

Phases which owe their Principal Features to a Combination of the Shearing and the Impregnation Processes.

SECTION 18. The hand-specimen is colored blue-black; medium soft and friable. There is a well developed set of horizontal partings, or cleavage, but the faces made by the separation of the rock along these lines are not smooth, but are rough and pitted. The fact that the elevations of one face fit into the depressions of the opposite one shows that the development of this parting cannot have been due to a lateral pressure, or any other of the reasons which are usually assigned for slaty cleavage, but is only to be explained by the contraction of the whole rock. There is also a perfect prismatic jointing. On nearly every one of the surfaces there is a rusty yellow coating of calcite. The section is nearly opaque under the microscope, from the presence of the iron oxides. This is almost entirely magnetite, and what hematite is scattered through is a decomposition product of the magnetite, as is evident by its clustering along the lines of easiest oxidation. Certain small spaces, however, are occupied almost entirely by calcite. It may be in this case that much of the calcite existed in the rock from the beginning, and that the leaching out and the leaving of the siliceous and ferruginous ingredients have formed the present phase.

SECTION 27-A. *Variety 4.* Described on page 65.

SECTION 33-B. Described on page 119.

SECTION 80. Described on page 79.

CHAPTER VI.

GENERAL DESCRIPTION OF THE PROCESSES OF METASOMATOSIS.

We have now, by a comparative study of thin sections, determined the relation of each phase to every other phase, and thus have been able to construct perfect lines expressive of the stages of change, beginning with the least altered rock and ending with that which is most profoundly changed. By the study of the individual sections, moreover, we have been able to decipher its history in nearly every phase, and the putting together of these histories gives a complete account of the rock, from its time of formation, or as early as we have any trace, down to the present day. It is the object of this chapter to tell, in a connected fashion, the changes which have taken place, but every stage described and every fact dwelt upon has been ascertained from the study of the specimens, and is described under the special cases where it has been best exhibited. In connection with each process described, a consideration of those principles upon which they depend and a knowledge of which is necessary for their understanding will be made, while some of the larger principles, which have affected the whole rock, and not any stage to the exclusion of others, will be reserved until later.

The primary rock, so far as the study of the sections goes, is a dark-green, slightly pleochroic substance, polarizing sometimes after the aggregate fashion, and at other times remaining quite dark under crossed nicols. In the less altered phases this occurs in compact masses, rounded or angular, averaging perhaps one-thirtieth of an inch in diameter, and closely crowded together in a siliceous ground-mass. The exact original nature of this substance is not necessary for an understanding of the changes which it undergoes and the rock to which it alters, for these changes are strictly the result of observation, and not theory. Indeed, the nature of the substance was not definitely known to the writer until the processes here de-

scribed had been fully worked out. In the notes this has been designated by the term "greenish chloritic substance" and that name will be retained for the present. This substance is not usually found fresh, for very soon it begins to become opaque from decomposition. The most notable results of this decomposition are the separation of finely divided silica, and of hematite or limonite. This process goes on in the following manner: At the very first the green material takes on a finely mottled appearance, due to slightly darker and lighter parts. These next arrange themselves in a number of tiny dark rings, scattered plentifully over the whole area. Under high magnifying power, however, these rings are seen to be really transparent, and to be composed of a very fine ring of silica. These rings steadily grow, in both directions, till in the last stage they meet and form a continuous mass of silica. This silica is at first nearly amorphous or apparently isotropic, but soon it begins to assume a faint cryptocrystalline structure, due to the individualization of the grains. These grains grow steadily larger and become coarsely cryptocrystalline or, very often, pass into the radiating fibrous chalcedonic condition. From these states they gradually, in the end of the process, crystallize as quartz; generally in interlocking grains with irregular outlines; but in rare cases there can be determined a certain hexagonal outline for some grains, so far has the crystallization gone. (See Plate VI, Figs. 1 and 2).

In proportion as the silica separates out from the green chloritic substance, that portion of the original material which remains becomes darker and more opaque from the separation of iron oxide, so that when the decomposition is complete, and the original substance has disappeared, the chief products are silica and hydrated iron oxide. Calcite is also a very frequent minor product, but, on account of its solubility, it usually disappears about as soon as separated; so that it is not an important permanent constituent of those areas which represent the bodies of the original material. This condition, in which rounded or angular fragments made up of iron and finely divided silica, in a ground-mass of silica (which is also finely divided, but almost invariably a little coarser than that of the granules, in whatever state this latter happens to be), is by far the most common among the multitudinous phases of the rocks of the iron-bearing member. The change of the silica from this phase is in general a gradual increase of coarseness, without great changes of position, till at last the degree of division becomes

not perceptibly different from that of the ground-mass. Thus they seem to merge, and the original outlines of the granules, so far as these are determined by the difference of the silica, are destroyed.*

THE IRON OF THE GRANULES.

The iron, on the other hand, marks every slight change of conditions which the rock undergoes by a change of form. Thus from its *original* (?) form of hematite or limonite it becomes a carbonate or magnetite, with or without concentration into crystalline forms. Subsequent changes bring this siderite or magnetite back to the hematitic or limonitic condition, and thus the fluctuation is kept up indefinitely. But as each condition of temperature or oxidation is very often not long enough to completely bring all the iron to the condition in which it would be most stable under its influences, there result from these changes curious mixtures of the different forms of iron, such as concentric rings, which are made up of siderite, magnetite, hematite, and so on. In certain of these stages the more soluble portions are apt to be dissolved out, in which case the space is filled by silica; and the alternating rings of the less soluble magnetite, hematite, and silica form granules the history of which is more complicated than ever. Thus, in 33-A, the hematite which is the very latest of the forms may be traced from an original magnetite through six intervening changes of form, so that it is the eighth of this line; and since it must be that the original magnetite was in its beginning derived from the hematite or limonite which forms by decomposition of the green chloritic silicate, it must be the tenth at least, since the iron was in the form of the silicate. It is quite probable, moreover, that the actual number of changes may be in some cases many times this. But with each change there is usually a little of the iron taken into solution and carried away, to be deposited

*An additional analysis of this type of rock is that of Specimen 107, a siliceous spotted-granular rock.

ANALYSIS OF SPECIMEN 107 (CHEMICAL SERIES NO. 243) BY A. J. HAMMOND.

		Per cent.
Silica.....	SiO ₂	57.00
Protoxide of Iron.....	FeO	11.08
Sesquioxide of Iron.....	Fe ₂ O ₃	27.05
Alumina.....	Al ₂ O ₃	1.43
Lime.....	CaO	0.40
Magnesia.....	MgO	2.02
Potash.....	K ₂ O	0.113
Soda.....	Na ₂ O	0.397
Loss by Ignition.....	.....	0.91
Total.....		100.4

elsewhere, in positions independent of the granules, and thus these bodies become steadily poorer in iron, and this distinction between them and the ground-mass becomes continually slighter. Finally they are quite deprived of all their ferruginous matter; and by this time, or soon after, the silica of the granules has usually become so much altered as to merge into that of the intergranular spaces. Thus all traces of difference disappear, and this part of the rock passes into a true chert, without any spotted-granular structure. The iron which has been leached from the granules has been carried on in solution till it reached a favorable place for precipitation, and the accumulation of these precipitates has brought about a concentration of the iron into a solid mass, which has usually the habit of a band.

Banded Jasper and Iron.

When the silica and the iron are thus completely separated into bands, the other constituents of the original rock having usually by this time been dissolved out, the normal process of change leads to the complete crystallization of both the silica and the iron. So the silica becomes a crystalline "jasper" which, if nearly pure, may be colored white or gray or, according to the impurities of iron, may be colored red, if impure with disseminated hematite; or black, if with finely divided magnetite. The iron becomes a crystalline hematite or magnetite. This last stage is the familiar "jasper and ore" of the iron regions, or "jaspilyte." The term "jaspilyte" cannot properly be used to designate this rock, however, since as now understood, it in no sense corresponds to the definition which was assigned it by Dr. Wadsworth in proposing the term.* When the silica is phenocrystalline, moreover, the word "jasper" is not strictly correct, since, according to Dana, jasper is one of the cryptocrystalline varieties of silica. But since this term has never been carefully restricted, and since the silica of the iron-bearing rock varies from phenocrystalline through all the transition stages to very finely cryptocrystalline, so that in any given specimen the two may be found intermingled, and since the distinction between the different varieties is often with difficulty distinguishable in the hand-specimen, it may be as well to still retain the term in this case. It will then be

*The term is proposed by Dr. Wadsworth, in the Bulletin of the Museum of Comparative Zoology at Cambridge, Vol. vii., p. 76, as follows: "We would propose, therefore, that all the acid eruptive rocks whose chemical and physical constitution carries them above the rhyolites, should be designated *Jaspilites*, from *jasps* and *lithos* in accordance with a suggestion of Professor Whitney.

understood that the word "jasper" in reference to the iron-bearing rocks refers to a cryptocrystalline, chalcedonic, or phenocrystalline silica, rendered gray, red, brown or black by various forms of iron oxide in various proportions. In that phase of the rock which is called "banded jasper and iron" the silica may be stated to belong in general to the phenocrystalline variety.

THE SILICA OF THE GROUND-MASS.

The silica of the ground-mass goes through the same process of concentration and crystallization as does that of the granules. When we first find it, it is very finely divided, but the grains tend to grow larger, and so in general we find that the silica of the ground-mass is a little coarser than that of the granules. This is due to the fact that the silica of the intergranular spaces has been formed first, and has been first started upon the process of crystallization. But it must be believed that much of this silica has had the same source as the similar and intimately associated silica of the granules, namely, the decomposition of a silicate. Whether this silicate was originally in the place now occupied by the intergranular silica, or whether the silica was separated in another part of the rock and was subsequently brought to its present position, is a question which must be separately decided for each case.

Nature of the Silica.

There is occasionally a variety of silica which appears quite dark under crossed nicols. But, very often, in this case the highest power may detect very small points of light and dark which belong to the extremely tiny individuals. From this condition there is a very perfect transition to the coarser cryptocrystalline varieties, thence to the chalcedonic or phenocrystalline stage. The relation of these different varieties in the same rock has been often observed, and shows that the coarser kinds are formed from the finer, normally, under the influence of the crystallizing motive. It must be suspected, then, that those cases which do not show any individualization of the silica under the highest powers, are not really amorphous, but consist of an aggregate of individual grains of sub-microscopic size. The crystallizing motive must begin to operate upon the mineral as soon as it is separated from the original silicate, and so there can be little or no truly amorphous or colloid silica in the rock. In a similar rock from the

Gogebic, Irving and Van Hise* have concluded that a part of the silica was really amorphous, "as shown by its ready solubility in caustic alkalies." But the solubility of silica by these agents cannot be said to be restricted to the amorphous variety. According to Roscoe and Schorlemmer,† "In all three conditions" (quartz, tridymite and amorphous silica), "silica is insoluble in water, and also in all acids except hydrofluoric, in which it readily dissolves. Silica, however, is easily soluble in all alkalies, even in ammonia, and the more readily the finer its state of division. The amorphous variety, especially if it contains water, also dissolves in alkaline carbonates." In these rocks we find that all the silica is liable to solution during the processes of change, and the chief difference in solubility of the different varieties appears to lie in the different degree of coarseness. We may assume, therefore, that while the immediate product of decomposition of the original substance must be in the very beginning of an amorphous nature, it begins to crystallize so soon that we have no appreciable amount in the rocks.

NATURE OF THE NORMAL PROCESS.

The very slow and gradual change from a dark-green silicate to banded quartz and iron, which, on account of its being the usual change, and apparently inevitable under the commoner conditions in the rocks, has been called the normal process, divides itself into two chief actions, the first degenerative, and the second regenerative. The degenerative action consists in the decomposition of the original material, and the result therefrom of a confused mass of silica, iron, and the more soluble products. From this the regenerative force begins to act, and operates to assort, concentrate, and crystallize these materials in their most stable forms. These two processes usually are going on together in the same specimen, and so intimately mingled are the products of these opposing forces that it is certain that they take place under the same conditions of temperature, oxidation and the like. The conditions were probably *a very scanty access of atmospheric agents*. We can find many evidences of the small quantity of the agents which have brought about these great changes. In section 53-1, the decomposition of the silicate was seen to be going on side by side with grains of apparently original carbonate, and so weak were the forces in

*Tenth Ann. Rep. U. S. Geol. Survey, p. 384.

†A Treatise on Chemistry. By Roscoe and Schorlemmer. Vol. I, p. 569. New York, 1882.

is case that the carbonate had been not at all affected by time. A very positive proof is in the remaining of the iron which is a result of the decomposition in the same place for so long a time, without changing form in any great way. Had there been free access of percolating waters through the whole rock, the iron would be carried out of the granule about as rapidly as it was separated. Again, the alternating conditions brought on by changes which must have been separated by very long periods often failed to convert the whole of the iron to the state which was most stable under their respective influences, as is shown by the successive rings of siderite, hematite, and magnetite. When there is, for instance, a rim of siderite around a residual core of magnetite, and the siderite is bordered in its turn by a rim of hematite, we may understand that the duration of the carbonatizing period was only sufficient to carbonatize a portion of the magnetite before conditions changed, and the oxidizing period began. But the events which brought about these changes of conditions must have occurred at long intervals. Thus the carbonatizing period in this cited case may really represent an immense period of time, and the paucity of its results shows that the action, and hence the amount, of altering agents was very slight. Under freely oxidizing forces, moreover, the crystallization of the cryptocrystalline silica will not take place, but, on the contrary, a disintegration to a powder. It is apparent, then, that the original substance was of an extremely unstable nature, and quite different in nature from the ordinary silicates of the rocks. The decomposition of silicates, with the separation of silica, and the removal of the more soluble products, is a well-known fact.* But in this same region, in contact with the iron-bearing rocks are granites, schists, and shales, in which the decomposition of the silicates since the Animikie period has been very slight, and has in no way obscured their original nature. Now the analysis of certain of the specimens† from the iron-bearing member, selected for their content of the original silicate, show that this mineral may be, in part or in whole, in its original state, a *ferrous* silicate. Here, perhaps, is the secret of its sudden and complete change. A ferrous silicate would be extremely unstable under very slight atmospheric influences, for the presence of a small quantity of oxygen alone would be sufficient to cause its disintegration.‡

* See Geikie, Text-book of Geology, p. 344. Third edition, 1893.

† See pages 87 and 103.

‡ See J. P. Kimball. Quoted in Iron Ores of Minnesota. N. H. and H. V. Winchell

THE FORMATION OF THE GRANULES.

The characteristic, peculiar and constant structure which belongs to those phases of the iron-bearing rock which have been operated on only by the normal process of change, except the extremely altered phases of chert, and jasper and iron, is that which has been designated in the descriptions of the sections as spotted-granular. Briefly, a description of the essentials of this structure is as follows: There is a ground-mass of finely divided silica, generally coarsely cryptocrystalline, but often finely cryptocrystalline, fibrous chalcedonic, or finely phenocrystalline, or composed of all these varieties intermingled in the same section. In this ground-mass are thickly crowded small bodies, which are generally darker, and so give a mottled and fragmental appearance to the hand-specimen. These bodies are, perhaps, on the average, one-thirtieth of an inch in diameter; in shape they are rounded or subangular, sometimes sharply angular. They are composed of silica, which in general is cryptocrystalline and more finely divided than the silica of the ground-mass, with siderite, hematite, limonite, magnetite and the green silicate, in various proportions and combinations. These principal constituents are typically without crystal form, although in many cases the magnetite or the siderite has crystallized. Besides these there are various subordinate, accessory, or secondary minerals, such as calcite, actinolite, apatite, (?) epidote, pyrite and clayey matter. All the minerals may occur in the same body, or the body may be composed of a single one to the exclusion of all the others. To these small bodies the name *granules* has been applied, and this term covers all, and has no reference to their origin. For all the granules have not been formed by the same cause, although they come to resemble one another; and in the more advanced stages they often cannot be distinguished, owing to the growing decomposition and change of their original outlines and structures. At least four different kinds, however, having each a totally different origin, have been described:

I. Concretions.

The granules derived from the process of concretionary growth have had their material drawn from a disseminated state through the rock, and concentrated around a common nucleus. The ball thus formed may be all of one material, such as hematite, or, owing to changing conditions, it may ex-

hibit a series of rings, one within the other, of alternating minerals. The concretion of the first class is, except at its very freshest stage, hard to distinguish from granules formed in other ways, and the ringed concretion may become so altered that its structure is hardly discernible. The principal of molecular affinity must be appealed to as the cause of these structures, for there seems to be little difference in oxidability and other conditions between the parts of the rock whence the mineral is drawn and the part where it is concentrated. But it is well-known that a mineral which may be in solution under certain conditions, will be precipitated if the solution is brought into contact with a solid mass of the same mineral, the molecular attraction between the mass and the mineral which is in solution being stronger than the power of the solvent. So in these concretions, solvents have taken the minerals into solution, and have carried them till they encountered the growing concretion (at whatever stage of growth, from the simple nucleus up), and there have deposited their burden. See Plate VII, Fig. 2.

2. *Spherical or Ringed Impregnations.*

The formation of these, contrary to that of the concretions, depends upon a greater degree of oxidation in the impregnated spot than in the other parts of the rocks. In these spots the conditions are no longer those typical of the normal process, but the changes have brought it about so that in certain spots scattered through the rock there is a weakness, which permits the readier access of oxidizing agents. In the normal condition, where the atmospheric influences are feeble, the iron is much more easily soluble than the silica, and hence is dissolved and carried away, leaving the undissolved silica still marking the outlines of the original granules. But when oxidation is freer the process is reversed. Instead of having the iron replaced by silica, as in the normal process, the iron is precipitated and the silica is carried off in solution. The chemistry of this process will be considered under the formation of the ore-deposits, in which it is the most important factor. So when the iron which has been taken into solution in various parts of the rock encounters one of these weak and highly oxidized spots, it is precipitated, and the water then takes up some of the original silica of the weak spot, and carries it off. The area of weakness may be a narrow strip following a ringed crack, either opened or incipient, or it may be of irregular or spherical form. In the first case the result is a ring, in the second a ball of iron oxide surrounded by silica.

3. *Original Detrital Grains.*

Original detrital grains of whatever material come under this head, for very soon they become so much altered that it is impossible to distinguish them from the granules formed in other ways. Such grains of quartz have been discovered by the writer once or twice, near the contact of the iron-bearing member and the underlying quartzite; original grains of carbonate have been found in one case, at the extreme upper surface, within a few inches of the overlying shaly carbonate; and in certain of the freshest sections it appears that the grains of the greenish silicate owe part of their form to attrition before consolidation.

It seems probable that the larger part of the granules owed their existence originally to this action; although the immediate forms, even of these, are in the latter stages generally partly or wholly due to one or more of the other processes described. See Plate V, Fig. 1; also Plate VIII, Fig. 1.

4. *Granules owing their Immediate Form to Brecciation.*

The great and constant changes in the chemical composition of the rocks have produced incessant changes of volume and consequent incessant strains. Since these strains have been of very slow growth, there has been usually an opportunity to relieve them in proportion as they are generated, by change of position distributed minutely throughout the entire rock,—by interstitial movement, in other words. By the effect of these constant motions the granules may be in places repeatedly broken up and divided, or again pressed together and consolidated. The change of mineral composition is an accompaniment and a promoter of this process. The change in form of the iron from a carbonate to hematite, when there is a shrinkage involved in the loss of carbon dioxide; from hematite to limonite, when there is an expansion due to the introduction of the combined water; the change of limonite to magnetite, when there is a contraction; from magnetite to siderite, when there is an expansion,—these are very powerful factors in bringing about this minute brecciation. The process of crystallization of the silica is hardly less important. But the action begins in the very earliest stage of the rock's history. When the original silicate decomposes, there is a contraction which goes on progressively with the decomposition, owing in the most part, probably, to the loss of those more soluble products which are removed about as soon as separated. In consequence

of this, the original grain becomes seamed and cracked; along these cracks the silica collects, as little veins, and begins the crystallizing process, and as this process goes on, forces the fragments wider and wider apart, from the accession of new silica. Between the silica of these veins and the iron, which has been separated and has collected into bunches in the separate parts of the original round grain, reactionary processes bring about the growth of various secondary minerals, chiefly actinolite. These borders of secondary minerals sometimes become very deep, and complete the separation of the original granule, and the formation of the new ones. At the first rending apart the outlines of the fragments are angular, but the uniting of the siliceous ground-mass with the ferruginous minerals of the granules to form the new minerals rounds the outlines, as well as reduces the bulk. In bringing about this effect the corrosive action of the silica upon the iron, which it often replaces around the borders of the granules, and the impregnation by the iron of the weaker spots of the silica, are also very important. So the form of some granules is altered, at many stages of the rock's history. See Plate V, Fig. 2.

It must be remembered that occasionally two, three or four of the processes described have operated to form a single granule as we find it. Impregnation may form a blotch of hematite in the silica, concretionary action may enlarge it, and, finally the brecciation may rend it apart and give it subangular outlines. These new granules may in their turn be made the nuclei of new concretionary action, and so the process goes on indefinitely. When a granule which is composed mainly of iron is leached by the action of waters, this iron is replaced by silica, molecule by molecule, and the silica which thus replaces it is as finely cryptocrystalline as that which arises from the direct decomposition of the silicate. Thus the presence of a finer grain of silica in a granule than in the ground-mass is not conclusive evidence that the granule represents the whole or even a part of one of the original green grains. As a matter of fact, although the grain of the granule is in general finer than that of the ground-mass, there are exceptions, where the silica is the same in both cases, and occasionally that of the granules is the coarser. In this last case it is probable that what was once the ground-mass has, by frequent division and brecciation, become the granules, and along the crevices has crept in from solution the later silica, which now forms the ground-mass. Indeed, this process is often seen going on.

This peculiar type of brecciation, produced by chemical forces slowly generated, producing strains which gradually are relieved by small interstitial movements throughout the whole rock, may be called a *granular-breccia*. It is not usually necessary to separate the varieties of granules in the rock, and in the advanced stages it is not usually possible without careful microscopic study, and then only in those cases where a single process has operated to the exclusion of the others, and where the traces of its action have not been obliterated by subsequent forces; but where this is desirable, the granules may be designated, according to the principle which had the most to do with their forming, as *concretion-granules*, *impregnation-granules*, *detrital-granules*, and *breccia-granules*.

COARSE BRECCIAS.

It often happens that, owing to the nature of the rock in which the strains are generated, the tension cannot be relieved little by little, and so accumulates till there is force enough to overcome the resistance of the rock mass. When the rock finally does give way the catastrophe is of much greater magnitude than in granular-brecciation, and produces a violent crushing and breaking up of the rock, into fragments of all sizes (Plate IX, Fig. 2). The larger ones are often as much as two inches in diameter, and in general are sharply angular; from these there is every gradation down to the size of ordinary granules. Not only does this brecciation resemble on a larger scale, the granular breccia, but there is no other possible cause than tension due to chemical action which could have operated. R. A. F. Penrose,* in the discussion a chemical breccia in a manganese deposit in Nova Scotia, cites four possible causes of brecciation: (1) "The surface breaking of the rock and the accumulation of its fragments at the base of cliffs or along the coast; (2) the crumpling of the bed by folding; (3) the shattering of the bed by igneous action; (4) chemical action, either in the bed itself or in the associated strata." Of these the first cannot have operated, for in the rocks in which the breccias are found, the traces of any detrital origin are scant or lacking; the second can hardly have had any effect, for the Animikie strata have been left relatively undisturbed, since their formation; the third cause, igneous action, is here impossible, for there is no trace for many miles,

*Ann. Rep. Arkansas Geol. Survey, 1890, Vol. 1, p. 533.

of any igneous action since the Keewatin period. So, even were not the characters of the rock such as to make its origin quite plain, we should still be forced to fall back upon the explanation based upon chemical action. But in these breccias the origin is unmistakable. The cement which encloses the larger fragments is of the same material as itself, but more finely broken up, simulating a granular-breccia. The shapes of neighboring fragments often closely correspond, showing that the distance that they have been carried since their disruption has been very slight indeed. There is very often, around the fragments, a rim of crystalline vein-quartz, or a closely crowded mass of the fragments may be cemented together by the same material, or, less frequently, by calcite. This shows that when the brecciation took place there were left around the fragments and between them, very commonly, cavities which were often half an inch in diameter, and became subsequently filled with minerals from percolating waters. These frequent cavities could not exist, if the breccia were caused by detrital or by igneous action. They show that the condition of the rock at the time of the brecciation was so firm that as soon as the strain was relieved by the brecciation, it immediately became rigid, and so failed to fill the cavities which it had created.

We may clearly understand, therefore, what these conditions were. When the expansive strains which were generated by the chemical changes in the rocks, and which, on account of rigidity of the rock, were unable to discharge themselves little by little, as generated, had accumulated to a strength great enough to overcome this rigidity, the rock gave way, flowing in some degree, although cold, under the great pressure; but when the rigidity was too great to allow of movement rapid and complete enough, shattering into fragments of all sizes. When the strain was thus suddenly relieved the rock, which had been plastic under pressure, became suddenly rigid, and so the irregular cavities between the fragments were left unfilled, until the minerals borne in solution through the shattered rock filled them with vein-material.

It is to be remembered that this brecciation under expansive tension takes place only in the most rigid rocks, while in those of different conditions it may find relief in folding, faulting or shearing. These different effects will be discussed later.

The conditions under which the normal process (which we have been considering, and which leads from the original green

silicate in a ground-mass of silica to the impure chert, banded with iron oxide; and thence, by the crystallization process, to the banded "jasper and iron"), takes place, has been found to be a very scant access of atmospheric agents. But it has also been found that the nature of these agents has undergone many variations during the history of the rocks, so that at one time oxygen was the chief influence, and all the iron became hematite; at another time carbon dioxide was very powerful, and the iron of the granules became carbonatized; and, again, the advent of oxygenated waters reduced the iron to a limonitic condition. We must next consider the effects of these different atmospheric agents on those portions of the iron-bearing rock where, owing in part to original position, but chiefly to subsequent accidents, the supply of these agents was greater. These effects are seen, first, in the upper horizons of the iron-bearing rock, these horizons being the nearest to the evident source from which all these altering solutions have come; and, second, wherever strains have produced zones or spots of weakness which have given freer passage to these agents. The effects thus produced by the opening up of the rock to outside influences may be chiefly classed as two,—the carbonating influence and the oxidizing influence, according as the changing conditions bring about an excess of carbonic acid or an excess of oxygen. It may be stated, in general, that the change from one to another indicates necessarily no change of atmospheric conditions, but merely some change in the density or porosity of the rock,—the filling or opening of channels or fissures, or such accidents of comparatively trivial nature. The predominance of the carbonating influence may be considered, in general, to indicate a less degree of porosity than does the predominance of the oxidizing influence.

THE CHERTY CARBONATES AND SIDERITIC CHERTS.

Although all the phases of the normal process are liable to the carbonatizing process, yet in most of them the process goes on so slowly that it is rarely finished before another change of conditions removes this influence. But towards the last of the changes, especially when the disintegration and rearrangement have proceeded so far as to allow the separation of the silica and the iron into separate bands or areas, the rock becomes permeable to a degree sufficient to permit the complete altera-

tion of the iron during a single period of carbonatization. Thus the impure chert and the siliceous bands of iron with which the chert is apt to alternate roughly, which, if the normal process continues to operate, pass into the banded "jasper and iron," become the alternating bands of "cherty carbonate and sideritic chert." The change is simply the carbonatization of the iron oxide in the rock, which then crystallizes as siderite. The iron oxide which has been concentrated into bands furnishes the bands of nearly pure siderite, mingled perhaps with what silica the iron had not yet replaced. The scattered oxide which gave the chert its dark color is concentrated into occasional crystals which are disseminated through the rock, sometimes thickly, sometimes very rarely, according to the amount of impurities which were residual in the chert, at the time of carbonation. The stages of this process have been minutely observed and described in the detailed description of sections. Slide 329 P. C. shows a good example of the carbonatizing process, about three-quarters accomplished, the residuary patches of limonite being scattered both through the chert and the carbonate. See Plate VII, Fig. 1.

THE OXIDATION AND CONCENTRATION PROCESS.

When by virtue of original location, subsequent accident, or otherwise, any portion of the rock is so situated that it becomes freely accessible to oxygen and the other forces of the atmosphere, the influence of carbonic acid is not able to leave much visible effect upon the rocks, but all the processes of decay and concentration are hurried forward with great rapidity. We may cite four principal causes which have operated to bring those rocks which we find at the present time to have been affected by this action, under the oxidizing influence. The first is original position, by which those layers which lie uppermost in the strata are first affected by the effects of the atmospheric agents penetrating downward from above. The second is erosion, which by its gradual action brings those parts of the rock which were once deeply buried to the surface. The third depends upon the folding and faulting of the whole series of Animikie strata, due to extraneous dynamic forces, which is exemplified in the fault at Virginia, and the associated disturbance of the strata. This action opens up great fissures and develops areas of special weakness, in any part of the rocks, so that the oxygenated waters can enter. The fourth consists

of faults, fissures, fractures, or areas of weakness, produced by strains generated within the iron-bearing member itself, and depending upon forces exerted by chemical changes in the constitution of different parts of the rock.

But from whatever cause induced, the effect of this action is in the end a complete disintegration, and a more complete separation and concentration of the more important constituents than in the normal process. The rocks which directly result from this are much decomposed or pulverulent, and, typically, there is an entire lack of any crystallizing action. When the oxidation process begins to operate upon a rock of the normal series, the iron speedily becomes transformed to the limonitic state. This accession of water usually produces an expansion, which affects the rock, in its porous and weakened condition, not by producing interstitial re-arrangements, but by a general loosening and a further development of crevices. The iron soon becomes leached out of the granules and distributes itself throughout the weaker parts of the rock. What remains finds its way in between the grains of silica, and thus, by wedging, attended by replacement of silica by iron along the edges, each grain becomes separated from every other, and the rock crumbles easily. When the iron has been entirely leached and carried away a nearly white, incoherent mass, consisting of almost impalpable grains of the silica, with usually, according to the stage in the normal process which the rock had attained before being subjected to the oxidizing forces, other residuary products. Notable among these is the residuary clay-like silicate of alumina, or kaolin, which is among the decomposition products of the original green silicate, and also of the secondary actinolite. Thus, if one of the primary spotted-granular rocks, or one of the ferruginous spotted-granular rocks which contains a good deal of actinolite, were subjected to rapid oxidation, the residuary product, after the iron and all the more soluble products had been leached out, would be a very finely divided mixture which would consist chiefly of silica, with some silicate of alumina. To this class, indeed, belong most of the pulverulent clay-like or shale-like parts of the iron-bearing rock. Usually the incoherent mass assumed a semblance of bedding or even slaty cleavage, apparently due to its own weight; by the pressure of its own weight, too, it assumes a certain firmness, which is often furthered by some slight cement of silica, lime and other minerals which percolating waters may bring. Specimen 70

(described on p. 81) is a good example of this residual clay. In this place, those lines of weakness which have been developed under the weight of the mass and which give the bedded appearance and shaly horizontal parting, have in many cases become the channels of iron-bearing waters from above, and, in consequence of the precipitation of some slight quantity of iron oxide have become brown, red or yellow bands in the white, according to the amount of iron which has thus become intermingled with the white powder. Usually, these bands are narrow, and white and colored stripes alternate at short intervals; but sometimes the clay has been uniformly stained for some distance. Often, indeed, the relative porosity may be about the same throughout the whole bulk of the residual mass, and it thus is stained with some uniform tint. Red is a common color, and the stained and consolidated powder simulates, and is generally called "red slate" or "red shale." Sometimes, especially in the vicinity of overlying Cretaceous beds, there is a green color imparted by the influence of the sulphur which occurs profusely in these latter deposits, and which leaches down into and through the porous strata beneath. Gray or drab, becoming in some cases nearly black, often results from the presence of iron in certain combinations, or of the oxide of manganese. An analysis of one of these gray pulverulent slates has been made, and, except for the condition of those constituents which make the coloring matter, the composition is essentially the same as that of the white pulverulent rock, No. 70, whose analysis is given on page 81. The gray rock, specimen 101, is from a pit in the southeast of the northwest quarter of section 18, T. 58-18. When taken from the pit it was nearly black, but on exposure to the air, or on heating, it became bleached to a slate-gray, owing probably to the oxidation of a part of the iron.

ANALYSIS OF SPECIMEN 101 (CHEMICAL SERIES 239) BY ALONZO D. MEEDS.

		per cent.
Silica.....	SiO ₂	61.57
Alumina.....	Al ₂ O ₃	16.83
Sesquioxide of Iron.....	Fe ₂ O ₃	5.27
Protoxide of Iron.....	FeO	6.41
Lime.....	CaO	0.01
Magnesia.....	MgO	3.44
Potash.....	K ₂ O	1.59
Soda.....	Na ₂ O	0.12
Water.....	H ₂ O	4.70
Total.....		99.94

Another specimen of the same rock, from this pit, which was suspected of containing manganese, was kindly tested by Mr. Joyce, of Mountain Iron, and found to contain over two per cent. of manganese dioxide. There is in this rock an alternation of lighter and darker gray in bands; and the contact of these is usually wavy and indistinct, showing that they are certainly due to infiltration into the rock, and were not present in its original condition.

These aluminous pulverulent rocks have been stated to be derived from those phases of the normal series which were not yet extremely advanced in decay, and so retained much of the original and little soluble aluminous constituents. When, however, a rock of the normal phase which has become definitely differentiated, that is to say, a chert with few impurities, becomes subjected to the oxidizing process, the result of the decomposition is a nearly pure silica powder. An example of this sort is found in specimen 230, which has already been described and of which the analysis is given later.

Amount of Residual Clays.

In the completely differentiated rocks of the normal series such as the banded chert and hematite, which, under the crystallizing motive, becomes banded jasper and crystalline iron; or even in that phase which represents the action of the carbonatizing influence, and results in the banded cherty carbonate and sideritic chert, the siliceous and ferruginous concentration areas or bands are not far removed from one another. For the porosity of the rocks is so slight that solutions travel but slowly, and hence the concentration is apt to take place near the spot whence the material in solution was taken. But in the parts of the rock which have come under the oxidation and concentration process the freedom of waters to penetrate every part of the rock becomes so great that the concentration becomes extremely rapid, and the more soluble constituents, notably the iron, are hurried on from point to point in the downward passage. So, finally, there is left at the surface a considerable thickness of the pulverulent residual rock or clay. Thus, in the pit whence specimen 70 was taken, there is a depth of 80 feet of this material; at the Mesabi Chief mine, there is a thickness of 11 feet of the powdered silica; at the Lone Jack mine, there has been found a thickness of 12 feet of a deposit similar to 70; and all over the Range are found surface deposits of "paint-rock" of considerable thickness. The

iron which is thus leached from the rocks above is of course collected and concentrated further on, in large bodies, which may become as pure or purer in iron than are the leached rocks, which represent the more insoluble portions, in silica. These concentrations of iron and other constituents thus belong to the series of oxidation and concentration rocks, and represent the ferrated rocks, as distinguished from the residual or leached rocks. As the extreme development of the leached rocks is in the white powder of silica or mingled silica and alumina silicate, so the extreme development of the ferrated rocks is in the bodies of pure iron-ore. On account of the importance of this subject, however, the fuller discussion of ore-deposits will be given special attention later.

THE SHEARING PROCESS.

It has been shown that strains in rocks too rigid to permit the gradual discharge of the strain by interstitial motion, may by accumulation finally produce a coarse breccia. If, however, there are certain layers or horizons in the rock under tension which are perceptibly weaker than those above and below, the accumulated strain, when discharged, will be confined in its effect to this layer. The result, if the layer is sufficiently firm and brittle and the strain sufficiently great, may be a brecciation as before; but more often there are lateral movements in these weaker layers, and the strain is thus relieved by changes in the intimate arrangements of the particles. This lateral movement, while the layers on both sides, on account of their greater firmness, remain rigid, results in the grinding into fine particles of the constituents of the rock, their intimate intermingling, and the development of a plane-parallel or schistose structure in place of the spotted-granular structure, which is in this process usually partly or often totally obliterated. If the layer is of considerable thickness and of uniform cohesion throughout, the strain, when it accumulates to that importance necessary to overcome this cohesion, will act upon all parts of the layer, and the effects of the shearing will be distributed with some uniformity. If, on the other hand, the zone of weakness is very narrow, the force of the discharging strain, compressed within such small compass, will profoundly crush the rocks of this zone, and very often will shear, crush, or brecciate, but to a less degree, the more rigid rocks which lie on either side. In general, the weakest part is a very narrow

zone, which often, so far as macroscopic observation goes, is a mere plane. This plane is, roughly speaking, parallel with the general banding, cleavage, and other horizontal structures, of the iron-bearing rock. The result of the pressure is to develop along this line an actual crack or slight fault-fissure, while the rock adjoining this becomes sheared, the violence of the action and the effect decreasing progressively as the distance from the plane of greatest weakness increases. Section 27-A is a good example of the different zones which represent the graded effect of the shearing force, within a short space. If, after this motion, the tension still continues, and the neighboring rocks are too rigid to be affected, the sheared zone may finally be brecciated; and in this case the fragments of the breccia will show, by their schistose structure, under the microscope, what their history has been. Section 33-B is a good example of this. Indeed, it seems that in the majority of cases there has been a certain degree of shearing previous to the brecciation, for the fragments generally exhibit under the microscope a linear arrangement and a deformation of the normal structure.

To recapitulate, the structure of rocks which have been subjected to shearing consists of a microscopic or macroscopic schistosity, which, when sufficiently developed, may be taken for slaty cleavage, but frequently is not noticeable in the hand-specimen; and the constituent minerals are finely divided and intermingled, without order of arrangement or, usually, any crystal form. There is, however, every gradation from the unaltered rocks of the normal series—through those which have been slightly strained and wrenched, so that the granules are elongated in a common direction, or sometimes wrenched apart,—to the typical sheared “slate.” The mineral composition of the sheared “slate” will depend, primarily, of course, upon the mineral composition of the rock of the normal series whence it is derived. But in the sheared rocks there are other important changes which alter the original nature of the minerals very much. One of these is dynamo-metamorphic action, which is attendant upon the crushing in the process of shearing. By this action various new mineral combinations, which did not exist in the original rock, are formed,—notably certain finely divided secondary silicates, such as chlorite and actinolite. A still more important effect of the shearing is to make the sheared rock porous and open to the passage of infiltrating waters. Thus the shear-zones become an active seat of concentration of the solutions from the other rocks of the iron-bearing

member; and, to a certain extent, apparently, of solutions from the strata which immediately overlie these rocks. The result is very often a filling of the sheared rocks with iron, which, under the conditions of free oxidation, as before stated, replaces the finely divided silica and associated silicates. The first effect of this is to penetrate along the planes of schistosity, as represented by the parallel lines seen under the microscope. These lines of iron oxide increase in both directions, till often adjoining lines unite, and the original chlorite or silica slate is transformed into a magnetite or hematite slate. Besides the iron, there is very often an infiltration of calcite, which, from the distribution of the rocks which are thus affected in the upper horizons of the iron-bearing member, is almost certainly derived from the calcareous layer of the upper slates, which immediately overlies. This calcite forms often an important part of the rock, being intimately disseminated through those rocks which are finely crushed and pulverized; and, when there is some slight degree of attending brecciation, forming the cement between the fragments. Later on in the history of the rock, when the iron-bearing solutions begin to penetrate, the union of the calcite and the iron takes place, with the production of iron carbonate, and the disappearance of most of the calcite. The replacement of lime carbonate by iron carbonate is one of the most familiar chemical actions in the study of economic geology, and need not be dwelt upon here.

THE IMPREGNATION PROGRESS.

The outline of this process and one of the principal methods of its operation has just been described, when considering the effects of lime-bearing waters upon rock which had been subjected to shearing. The presence of a cement of lime between the fragments of some of the breccias has also been already noted. And although the most conspicuous effects of this infiltration are usually associated with the rocks which bear the evidence of having first been subjected to the shearing process, yet often we have its work in the rocks of the normal series. This happens chiefly when the effects of internal strains have been such as to open many small cracks and interstices through the rock, without any actual shearing or even brecciation. The cause most likely to produce such an effect may be the reduction of siderite to hematite, or some such action. When the spaces (which are typically of about the same size as

the granules), are thus opened, they are filled with the calcite, and thus the rock is again firmly consolidated. Associated with this infiltrated calcite, wherever it may occur, there is generally iron pyrite, which, however, never is plentiful enough to be anything but a constituent of very small importance. When pyrite occurs without notable calcite, as it sometimes does, the source of the sulphuric acid by virtue of which it was formed may be the Cretaceous beds, which probably overlay at one time all of the iron-bearing rocks, as scattered patches here and there show. These beds are very rich in the sulphides, as a result of the organic matter which they contain.

CHAPTER VII.

NATURE OF THE AGENTS WHICH HAVE EFFECTED THE CHANGES IN THE ROCKS OF THE IRON-BEARING MEMBER.

We must now consider briefly the nature of the agents which have been availed of in effecting the enormous changes of chemical composition, which are so remarkably shown in the iron-bearing rocks. It is clear, however, that the initial cause of these great changes was in the original nature of the iron-bearing rocks themselves, and not in any very remarkable altering agents, for these same agents must have operated upon the other rocks with which the iron rock is so intimately associated,—the quartzite below, the calcareous and siliceous slates above, and the conglomerates and shales of the Cretaceous, while often the rocks of the iron series rest against the schists of the Keewatin, or the intrusive granite of the Giant's range. These allied rocks not only are not profoundly changed, but their freedom from alteration and metamorphism since the Animikie period is very remarkable, in view of their great age. We may in particular compare the other members of the Animikie strata, and here we find that there has been no great change in their internal structure, either mechanical or chemical, since they were laid down. The only important change which has taken place in the quartzite is the formation of the enlargement rims of silica which connect the original sand-grains and consolidate the rock; in the calcareous portions of the upper slates there has been some dolomitization and sometimes ferration of the calcite, but the original structure is usually well preserved, while in the siliceous slates the grains seem nearly as fresh under the microscope as when they were deposited. Since the iron-bearing member lies nearly horizontal and between the quartzite and the upper slates, any

agents which have operated upon it must also have been free to operate upon the other members of the series. So from the lack of any remarkable effect upon the other members, we must conclude that the agents in themselves, were by no means remarkable or unusual.

The Altering Agents Were Chiefly in the Form of Solvents.

Thus we see that the cause can neither have been heat nor great mechanical disturbance, for either of these forces would have metamorphosed the associated rocks as well. Moreover, there is at present no definite knowledge of any igneous rocks, later than the period of deposition of the iron-bearing member, on the whole of the Western Mesabi, or in its immediate neighborhood; and that no great mechanical disturbance has taken place is shown by the nearly horizontal, little-folded condition of the strata. In the study of the peculiarities of the change of the iron rock itself, everything: the increased alteration as the porosity increased, the beginning of the changes along cracks or joint-planes; and, in the intimate structure of the rock, the alteration of the iron from one condition to another, in a rim which began around the edges of the original mass, and worked inward,—these and many more phenomena show, beyond a doubt, that the agents were in the form of solvents, and that the chief vehicle of these solvents was a liquid, probably water.

The Waters Were from the Surface.

That the source of the waters which bore the solvents was from the surface, from which its course through the rocks was downward, obeying the forces of gravity, is shown by every characteristic. Wherever an opportunity, by borings or otherwise, is found to obtain a vertical section of the rocks, it is almost invariably the case that the most altered rocks are found upon the surface, and that the change which has taken place grows less and less as the distance from the surface increases. The pit in section 6, T. 58-17, already often referred to, is a typical case, where at the surface the rock is decomposed to a pulverulent mass stained with iron, to a depth of 80 feet, after which it passes by a series of gradual changes into the solid rock, arriving finally at a phase which is one of the first in the series of change. The silica powder at the Mesabi Chief mine has also been referred to. (Fig. 9). But these are only examples of what under normal conditions is an invariable

rule. All the pulverulent rocks, including those which have been partially consolidated and given some slate-like characters, and the common class of paint-rocks, are found at the surface and above all other phases. In ore deposits it is common to find a certain thickness of paint-rock immediately below the glacial drift. Typically, there next follows a paint-rock rich in hydrated iron, which is denominated yellow ochre; next a thickness of the pure ore, but of the yellow, hydrated variety, and finally the granular blue or brown hematite. Sections of test-pits at the Biwabik mine, which are nearly typical, and

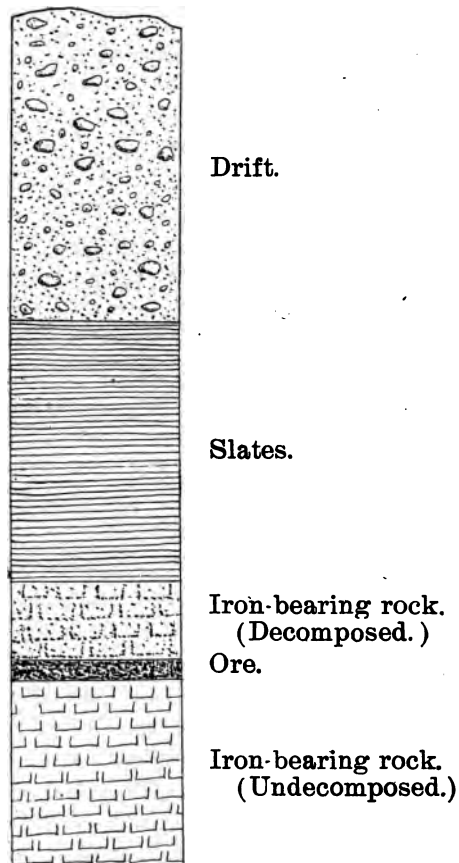


Figure 10.

Section illustrating a boring near McKinley, on Sheridan property.

illustrate this principle, are given in the Twentieth Annual Report of this survey.* This decrease of alteration as the distance from the surface increases also appears to hold good

*Horace V. Winchell. The Mesabi Iron Range, plate I, opp. p. 136.

even when the iron-bearing rocks are protected by a considerable quantity of the overlying slates. Mr. H. V. Winchell has furnished me with specimens and the record from a drill-hole in the swamp which lies immediately east of the town of McKinley. This passed through the slates, which here overlap the iron rocks, and through a considerable portion of the iron-bearing rocks beneath (see Fig. 10). This section not only demonstrates the fact that the altering agents were surface waters but, incidentally, it emphasizes the fundamental difference between the iron rocks and the slates, in that, although a large part of the solutions must have been obliged to pass down through the slates in order to reach the strata beneath, yet they have had no visible effect upon them. Had there been no marked original difference between the two, and had the agents themselves brought the causes of change, we should find the slates most altered of all.

Second, in exposed sections, we may often trace the exact course of the percolating waters through barren rock, by the deposit of iron which marks the whole distance, in a band of varying importance. These records show a constant striving of the solutions to pass downward. They have always availed themselves of cracks, joint-planes, or fissures in their downward progress, but when opportunity offers they forsake a given fissure for one lower down. When there are no lines of special weakness, but the rock is equally porous throughout, the ferruginous solutions are seen to have worked downward, through the most irregular and tortuous channels. These solutions which are thus shown to have striven to work directly downward, represent, of course, those portions of the rock which were at the time above the surface of the ground-water level.* When this level was reached, the normal course of the waters became very nearly parallel to the surface of the comparatively impermeable underlying quartzite.

Third, we have, in this region of the upper surface, cavities, usually of small size, but of all shapes, into which these downward-moving waters have penetrated. The cavities are in their origin very evidently spaces of dissolution, where some more soluble portion of the rock, such as an area of concentrated carbonate in the midst of a siliceous rock, has been dissolved out. On reaching this air-filled space, the chalybeate waters lose the carbon dioxide, by virtue of which they held the iron

*See F. Posepny. The Genesis of Ore Deposits, p 17. (Trans. Am. Inst. Min. Eng., August, 1898.)

in solution, and thus the iron is precipitated as the hydrated sesquioxide, or limonite. This limonite forms coatings on these cavities, but they are rarely smooth. They typically have a botryoidal or mammillary surface, and often this structure develops into a true stalactitic and stalagmitic form. The stalactites and the stalagmites may grow until they meet, and thus form columns, slenderest in the middle and widening toward the bases. This is very common on the Mesabi, but I have not seen it here in such large masses as in specimens from other iron regions, where among miners it goes by the name of "pipe ore." The stalactitic structure is peculiar to the vadose on surface circulation.

These same stalactitic growths are very often found in the silica, formed under the same conditions and having the same aspect. These occurrences show that the course of the silica-bearing solutions was the same as that of the iron-bearing solutions. Another important corollary of this is, that the original silica was freely soluble, under certain conditions, in surface waters.

NATURE OF THE AGENTS WHICH THE WATERS HELD IN SOLUTION.

From our study of the different sections, and of the rocks from which they were made, we may speak with a good deal of accuracy concerning the nature of the agents which have been availed of to produce the changes. We may also distinguish, from their comparative effects, the order of their relative abundance.

Oxygen.

Of these *oxygen* has had the greatest effect. Its work is seen in nearly every phase of the rock. In the normal process of change, it is very important, and in those rocks which have been called oxidation and concentration phases, it is the chief factor. The rocks of this latter class, too, are very widely distributed. To oxygen in particular we may in the first case ascribe the decomposition of the original silicate, where the separation of the iron sesquioxide shows its presence, and continually, through all the stages of change, we find it recurring and predominating over other factors, bringing about the oxidation of the iron. Finally in the exposed spots which are continually multiplied with time, it brings about the entire and rapid change and decomposition of the rock, pro-

ducing, in the concentrated silica powder or residual clay, and the concentrated iron powder, rocks which can no longer be greatly altered by its effects.

For this oxygen there is only one probable source—the atmosphere, from which it was brought in solution by atmospheric waters.

Carbonic Acid.

Scarcely second to oxygen in importance has been the effect of carbonic acid. This has been no less constantly present than oxygen, wherever opportunity offered. To it is due all the carbonates, chiefly siderite, whose continually recurring periods of formation are quite as numerous as the periods of oxidation. Indeed, the number of changes from the carbonating to the oxidizing motive, in the same rock, without any striking change of conditions, shows that these changes were dependent on very slight variations, and that the two agents were associated in the very closest way. Carbonic acid undoubtedly played an important part in the decomposition of the original silicate, and where it was predominant the iron separated out immediately as carbonate.* In the arrangement and concentration of the constituents, such as the iron and the silica, its work has been of the utmost importance, for undoubtedly it has been the chief carrier of iron. The amount of siderite is no test of the importance of this work, for most of the oxide also has been precipitated in this form from solution in water containing carbonic acid.

We have shown that the source of the carbonic acid was from the surface, and was connected with the oxygen. The sources of carbonic acid at the surface at the present time are well-known and various, and these must have been present continually since the formation of the iron-bearing rocks. The most important supply is perhaps volcanic action; but, secondarily, the action of decaying organic matter supplies an enormous quantity. That organic matter was present from the time of the formation of the iron-bearing rocks is shown by the amount which analyses show to be still present in the overlying Animikie slates; and the Cretaceous beds are very rich in this. We also have evidence of the existence of volcanoes at this and at earlier periods.† Finally, a very important source of supply

* Geikie. Text-book of Geology, 1893, p. 344.

† G. M. Dawson, British N. A. Boundary Commission, 1875; A. C. Lawson, Geol. Survey of Canada, vol. III, pt. I, 1888; N. H. Winchell, Geol. and Nat. Hist. Surv. of Minn., 15th Ann. Report, 1887; 16th Ann. Report, 1888; Bull. No. 6, 1891; U. S. Grant, Geol. and Nat. Hist. Survey, 21st Ann. Report; M. E. Wadsworth, Geol. and Nat. Hist. Survey Minn., Bull. No. 2, 1887; C. R. Van Hise, Bul. Geol. Soc. Am., vol. 4, p. 435.

in this particular case has been in the thin bed of impure limestone which immediately overlies the iron-bearing member. While this has, in general, preserved its structure, analyses show that it has undergone certain chemical changes, of which dolomitization and ferration are examples. From the original lime, acidulated waters from the surface must have liberated carbonic acid in considerable quantities. These are the original sources of the carbonic acid, but once within the iron-bearing rock it was cumulative, so that at most periods of change the income exceeded the output. Thus when a considerable portion of the iron had been reduced to the condition of carbonate, and was thus precipitated at some slight distance from its original position, the subsequent oxidation of the carbonate procured a fresh supply of the acid, and so the process was repeated indefinitely, each step bringing the iron in a stabler form, under existing conditions.

All these changes can be seen going on at the present time, and, apparently, as vigorously as ever. There is therefore no evidence in these rocks that the supply of carbonic acid was ever greater, since all the phenomena are perfectly explicable by the action of existing waters.

Sulphuric acid.

The presence of sulphuric acid in small quantities is indicated by the iron pyrites which are scattered sparingly in the rocks of the iron-bearing member,—more sparingly, perhaps, than in ordinary slates. We must therefore believe that the effect of this acid has been very small, since it would otherwise have brought a larger quantity of the iron to the pyrite condition. Sulphuric acid has been shown* to be able to decompose silicates, such as feldspar and biotite, with the separation of free silica and the leaving of a residual clay or kaolin, which is the process of decomposition which the original silicate of these iron-bearing rocks has undergone. But this change is accompanied in general by the deposition of sulphides, and so it can have had no very great effect here. The influence of oxygen and carbonic acid has been seen to have been quite sufficient for decomposition in this case; and, as has also been pointed out, had more powerful agents, such as sulphuric acid, been present in large quantities, we should expect to find that the silicates of the green schists and the granite had also been decomposed. As to the source of what little there is in the rocks, much of it must come from the Cretaceous beds;

which, on account of their organic matter, have become rich in sulphur and the sulphides. This view is supported by the fact that those portions of the iron-bearing rock in which pyrite in notable amount is present are usually near to the Cretaceous beds.

The alkalies.

These have been very important as agents of change. They appear to be in some small measure derived from the decomposition of the silicates. Analyses show their constant presence in the rock, but only in small quantities. In proportion as the original silicate is replaced by its decomposition products, the content of the rock in alkalies generally becomes less, showing that these soluble elements had been removed in solution during the process of decomposition. But these alkalies, dissolved in water, have the power to take into solution the silica, in the finely divided and scarcely individualized state in which it separated from the green silicate; and hence they have had the greatest effect in its transportation and rearrangement. There are other more important sources. Surface waters dissolve from the soil continually a considerable quantity of alkalies, and these have doubtless found their way down to the iron-bearing rocks. During these periods when the rocks were under the ocean, sea-water must have penetrated these strata very freely, after the decomposition had once begun, and the salt in solution in sea-water had the power to dissolve the silica. Ammonia is constantly generated at the surface from the decay of nitrogenous organic matter† and is taken into solution by surface waters in the form of ammoniacal salts, which ordinarily have the power to dissolve silica‡.

Other Agents.

That there are other organic acids, about which little is generally known, which arise from the decay of organic matter and have in some cases had more influence in the decomposition of rocks than even carbonic acid, has been shown by Prof. A. A. Julien.§ Doubtless these have been efficient in the changes in the rocks of the iron-bearing member, but they must have been of secondary importance. The principal effects, to sum up, have depended upon oxygen, carbonic acid, and the alkaline salts.

*R. O. Hills, Proc. Colo. Sci. Soc., Vol. I., p. 20.

†Boecoe and Schorlemmer: Treatise on Chemistry, vol. 1, p. 453.

‡Ibid, p. 560.

§Proc. Am. Ass. Adv. Sci., vol. xxviii, 1879, pp. 311-410.

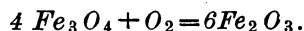
CHAPTER IX.

DEVELOPMENT OF CERTAIN PHYSICAL CHARACTERS OF THE IRON-BEARING ROCK.

We are now prepared to discuss the nature of certain of the most common peculiar features of the iron-bearing rocks. Chief among these may be enumerated; (1) the prismatic jointing; (2) the slaty cleavage or horizontal parting; and (3), the banding and bedding.

In previous pages we have discussed the origin of the spotted-granular structure, of the coarse brecciation, and the development of lines or zones of shearing; ascribing these effects to chemical changes in the rocks, which, producing expansion, generated an accumulating fund of expansile strains; and these when discharged, produced effects which differed according to the strength of the tension and the position and internal structure of the resisting rock. The chief cause of these expansile movements is believed to depend upon the change of a considerable quantity of iron oxide to iron carbonate. This may be ascertained from the nature of the rocks which have undergone these actions, in which we find sufficient proof that these chemical exchanges have taken place.

The increase of volume of the iron mineral by a change from the oxide to the carbonate may be easily estimated. If the first form was a magnetite there is generally a transition stage through hematite, which may be expressed chemically as follows:



In this reaction there is an increase in the weight of the rock, owing to the introduction of the new molecule of oxygen. The weight of this is less than four per cent. of the weight of the four molecules of the ferro-ferric oxide. This means that for every one hundred parts by weight of the magnetite there

are formed somewhat less than one hundred and four parts of hematite, by weight. But since the specific gravity of hematite is somewhat less than that of magnetite the total increase in volume is about four per cent.

The change from hematite to siderite may be expressed by the following reaction:



In this case the molecules of carbonic acid which are taken into composition to make up the siderite make up nearly one-third of the weight of the resulting mineral. This means that two parts by weight of hematite make up about three parts by weight of siderite. But since the specific gravity of siderite (about 3.8) is less (by about 1.1) than that of hematite (about 4.9), the increase in volume will be greater than the increase in weight. Thus we find that one volume of hematite produces very nearly two volumes of siderite, and one volume of magnetite almost exactly two volumes. Thus any rock which is composed exclusively of iron oxide, which is converted entirely into the siderite must expand to just twice its former volume, by means of interstitial movements, or disturbances on a larger scale. But there are no large areas in the iron bearing rocks where this change can be affirmed to have taken place, which are made up exclusively of the iron ores. It may be estimated that on an average about twenty per cent. of the rock is made up of iron oxides, the rest consisting chiefly of silica, with the silicates. In this case, the whole rock increases by about one-fifth of its former volume. There are many rocks in which the amount of iron oxide is as much as thirty per cent., and many others where it does not rise above ten per cent.

If in the rock which contains only twenty per cent. of the iron oxides, only half the iron were carbonated, there would still be an increase of volume of one-tenth of the former bulk. It is to this action, therefore, that may chiefly be ascribed the various brecciating and shearing movements in the rigid rocks. Faulting is also occasionally developed under this strain, but in the rigid parts folding is very rare, for the rocks are so brittle that they will not permit being bent. This lack of crumpling shows that at the time of disturbance the rocks were by no means in a plastic state, otherwise folding would have been one of the most important results. In the ore-bodies, however, there is usually a very complete minor folding, but

as this takes place under different conditions, and in part at least from different causes, it will not be described until the special consideration of ore deposits.

Having considered the phenomena which result from the expansion incident to carbonatation, we may now consider the effects which are produced when in turn, by changing conditions, this carbonatized rock becomes again oxidized. There will, of course, result a diminution in bulk, corresponding to the former increase, and this results in various cavities, fissures and joint planes. One of the most important of these effects is the prismatic jointing.

THE PRISMATIC JOINTING.

This is also called *columnar jointing*, and the name may be applied here with perfect propriety; and it is identical in appearance, and also in cause, in so far that it is occasioned by a general contraction of the rock, with *basaltic jointing*, but this name can hardly be used.

One of the most convincing proofs that this columnar jointing, as well as the cleavage, the banding and bedding, and other phenomena, which will be discussed later, are wholly of secondary origin, is that they are found only in much altered rocks (which in their composition usually bear further proof of the exact nature of the chemical process) and that the fresher phases have no traces of any of them.

Jointing in rocks may be divided into two chief classes—those produced by forces not usually originating within the rock affected, but consisting of regional strains and tensions in the crust, from whatever cause induced; and those in which the movement originates and is confined in its effect to the rock itself. The first class is by far the commoner, for the strains which produce this class of joints are almost always present in the rocks, and in regions where there is any mountain-building going on they are particularly strong and frequent in their precipitation of catastrophes. The effects which they bring about are generally supposed to be directly due to torsion and compression of the rocks, as shown by Daubree,* or primarily to these tensions, and directly to earthquake shocks, as suggested by Crosby.† They result in series of parallel and inter-

*Geologie Experimentale, pp. 300-374.

†Proc. Boston Soc. Nat. Hist., xxii. 72-85. Also American Geologist, vol. xii. No. 6, December, 1893, pp. 368-376.

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secting joints. There are generally two principal series, which thus cut the rock, if there is also a horizontal parting present, into cuboid or rhombohedral forms; each joint-plane is persistent over large distances, and passes from one stratum into another, although the direction and importance of the parting may be changed or obscured, if the texture and firmness of the two strata differ in any great degree.

Joints originating in and confined to a single rock are usually caused by a contraction in bulk of the rock. While the regional joint planes, resulting from torsion or compression, are found in every kind of rocks, and are almost universally present, those which arise from contraction are chiefly found in those igneous rocks of an effusive or intrusive nature. These rocks, poured out as lavas, or injected as dikes among cool and consolidated strata, are rapidly cooled; in cooling there is a contraction resulting in part from the loss of heat, but probably also in great part from the loss of the gases which they are unable to retain under atmospheric conditions, but which might have been incorporated into the solidified mass, had the cooling gone on under the great pressure of the internal region. The universal shrinking results in the development of numerous joint-planes, all of which are at right angles to the cooling surfaces, and which by their intersection divide the rock into prisms or columns of nearly uniform size. Thus in lavas there is a series of prismatic or basaltic jointing which is always vertical; and in dikes the familiar columnar structure forms prisms at right angles to the walls of the dike. The shapes of these prisms are quite characteristic, and sufficiently identify their origin; in cross-section they are always polygonal, typically hexagonal; the thickness of the columns is not great, and the planes of jointing are smoother and more definite than in regional jointing. The joint-surfaces in prismatic jointing are not persistent, for since the immediate cause by which each one originated was confined to the two columns between which it forms a boundary, it has no necessary connection, and no strict parallelism with those planes which bound other columns.

The typical jointing of the iron-bearing rock has all of these characteristics. It always forms vertical polygonal columns, which are in many places one of the most conspicuous features of the rock. On the north side of Iron Cliff, in section 36, T. 59-17, this jointing of the hard siliceous rock and iron is well shown in pits; at Virginia, in a railroad cut on the property of the Ohio mine, it is found in a slaty and ferruginous variety

of the rock; and in section 20, T. 58-17, near the south quarter-post, there is a steep and bare cliff of the iron rock, here also somewhat slaty, which has a very perfect columnar jointing. This cliff is almost vertical, and faces the east. Its height; including the talus slope at its base, is not far from 170 feet. But the structure is quite constant in all the intermediate phases of the member, and is found to a greater or less degree of perfection in the rocks of nearly every test-pit or outcrop. It is absent only from the least altered phases and from those which are much decomposed and disintegrated. Thus it is clear that the cause of the jointing cannot lie in the cooling of a once molten rock, for if this were the case the structure would be best developed in the freshest parts, and become fainter progressively as metamorphism proceeded. There is also the negative evidence, of less value, that no trace of an igneous origin exists in the internal structure of any part of the rock. It must be, then, that these same processes of metasomatic change, with the evidence of whose work it is always associated, have also been connected with its formation; and when we find that those rocks which have been affected in this way are those in which the iron has been changed from the carbonate to the oxide, the exact cause is evident.

The great similarity of this jointing to the basaltic jointing of lavas is thus seen to result from the fact that they were formed under very nearly the same influences; like the lavas, the iron-bearing rocks have in these places undergone a diminution of volume, due in the iron rocks chiefly, in the lavas in part at least, to the loss of volatile gases; in both cases this diminution of volume has caused a contraction, and under the cohesive tension the rock has separated in its shortest diameter, which is therefore its weakest dimension. Since the iron-bearing member, then, lies nearly horizontal, the prisms are nearly vertical, running as they do perpendicularly to the surfaces of the strata. But while the jointing of volcanic rocks is formed somewhat suddenly, and accompanied by a great change of temperature, the jointing of the iron-bearing rock has taken place very slowly, and under a nearly uniform temperature.

We may further note a significant fact to prove that the cause of the jointing can be ascribed to no source but one originating in and confined to the iron-bearing member. The associated strata, lying above and below, show no trace of it. The upper slates appear almost free from any joint-planes; and the underlying quartzite is hardly better supplied, so that it

breaks into irregular blocks. Certainly, in neither is there any trace of the columnar structure. Had the jointing of the iron-bearing member been due to regional forces, the associated strata must have been affected as well; and the lack of this effect cannot be explained by the difference in texture and rigidity of the iron rocks from the others. For so varied are its phases that there are many localities, in which the columnar jointing is prominent, where the texture and rigidity is almost exactly that of the quartzite, and many others, where it is quite as perfect, where the qualities are almost exactly those of the slates.

THE SLATY CLEAVAGE OR HORIZONTAL PARTING.

Besides the prismatic jointing above described, there is present generally a rough horizontal parting, which divides the rock at right angles to the vertical separations. In perhaps the most cases, these horizontal joints are far apart, and do not play a very conspicuous part in the structure; but in certain phases they gradually multiply, till they are set so close together as to resemble the cleavage of slates. This peculiar cleavage is found in certain of the phases of the normal class, and in the less altered phases of these which belong to the oxidation and concentration class, so that it is very common. It is distinctly marked in the cut on the Ohio property at Virginia, in connection with the vertical jointing, and as well in the steep cliff in section 20, in the same township. It is also well shown in the harder portions of the rock at the Snively mine, in section 2, T. 58-18, and in hundreds of other localities. The peculiar structure of this cleavage-like jointing is as follows: Although the lines of division lie, in their general course, in one plane, yet the details of this parting surface are very irregular. Instead of there being two smooth, close-fitting, and absolutely parallel surfaces, there are on each surface numerous elevations and depressions, which fit perfectly into the corresponding depressions and elevations of the opposite surface; so that the line which marks the intersection of this parting with the vertical jointing, instead of being perfectly straight, is extremely irregular in its details, although tolerably regular in its general course. Moreover, the irregularities of two adjacent horizontal partings do not correspond; but seem to be quite independent of one another. The surfaces which are thus produced by these partings, moreover, are not

fine and smooth, but have a granular texture, and, in general, a somewhat porous appearance.

From these peculiarities it is evident that these partings can be explained by none of the usual methods of accounting for the development of cleavage. None of the processes induced by pressure can have operated, for the division planes resulting from these would be smooth and parallel. In slaty cleavage or schistosity, induced by pressure, the number of division planes is very great, and become actual cracks upon the application of a very slight force, while in this horizontal parting of the iron-bearing member the number of potential divisions appears in general not to be much greater than the actual fissures. Between these actual fissures the distance may be often a considerable fraction of an inch, and in this thickness there may be very little indication of any slaty cleavage, but the fracture may be the rough conchoidal-irregular sort which is so common in the iron-bearing rocks. Moreover, the perfect planes of the vertical jointing show that there has been no lateral pressure exerted since its formation. The horizontal cleavage of this sort is rarely without the vertical parting, and since it may be seen developing in the fresher vertically jointed rocks, by successive multiplications of the horizontal joint-planes, it thus seems always secondary and there could be at no stage any opportunity for lateral pressure to act.

The explanation of this cleavage, then, is simple, if the main conditions of its occurrence are borne in mind. To repeat, these conditions are: (1) it is associated with the vertical jointing, (2) its development is subsequent to the development of this vertical jointing, (3) the structure is not suddenly induced, but is gradual, beginning as widely separated horizontal partings, and growing by the multiplication of these partings, (4) the surfaces separated, along the partings, are rough, uneven, and interlock without any trace of friction, so that it must be that the force which produced the separation can have had no lateral movement whatever, but must have acted at right angles to the separated surfaces. Hence in any given fragment, bounded on two of its sides by these horizontal partings, the force which has operated upon the under side must have been directly opposite in direction from that which has operated on the upper side, and the two forces must have neutralized one another in a plane in the middle of the fragment, midway between and parallel to the two cleavage surfaces.

There is only one possible explanation which answers these conditions, the obvious one of general contraction through the whole bulk of the rock. They are the results of the continuation of the process of contraction (dependent chiefly upon the oxidation or dissolution of iron carbonate), which has produced the columnar jointing. The development of this prismatic jointing does not mark the cessation of contraction in the rock, but only a stage where the forces of contraction have accumulated to the amount sufficient to overcome the resistance of the rock-mass. After this catastrophe the contraction still goes on, if there is left in the rock any amount of unoxidized material. When the strain again becomes sufficiently great, the rock again separates, as at first, along its least diameter, which is the plane of greatest weakness. But at the development of the prismatic jointing the whole iron-bearing member was one compact body, and hence the line of greatest weakness which any general strain found was in the least diameter of the member as a whole, and so vertical to the general dip of the stratum; but when the effects of this first strain had parceled out the rock into a series of vertical columns, any subsequent contraction must first find relief in the shortest diameter of the mass of rock or column in which it originated, and hence the jointing would take place always at right angles to the original jointing. In the second process the forces of contraction may be supposed, for the sake of simplicity, to operate in six directions, each of which is parallel and opposite in direction to one of the other forces and at right angles to each of the other four. Diagrammatically, they thus represent the axes of a cube, and the forces all meet and counteract at the common point which is formed by the intersection of the lines—the center of the cube. Then, in the contraction of the prism of rock, the strain of four sides on the cube would be mainly relieved as fast as generated by a widening of the original fissures, and would necessitate no further partings. The only strains that could find no immediate relief, and hence must accumulate, would be those two which act parallel to the longest dimension of the prism, and parallel and opposite in direction with one another, and these would in time bring on the separation at right angles to the original jointing. This explains why the jointing of the secondary contraction results in the development of roughly parallel lines, instead of in the production of polygonal prisms. But it does happen sometimes, when the secondary contraction is extreme, that the enlargement of the

fissures of the first jointing cannot satisfy all the shrinkage, and hence there are developed a series of tertiary partings, parallel to the faces of the original column. These last are, naturally, tertiary in importance, as well as in relative age.

Besides this commonest variety of cleavage in the iron-bearing member, certain others have been before described, and need only to be mentioned. In the process of shearing, there results, from the interstitial movements of the rock under a strong lateral force, a genuine cleavage, or schistosity. When sufficiently pronounced, this cleavage may be well-marked macroscopically, especially when it is developed by concentration of iron oxide along these lines of weakness. In completely decomposed pulverulent rocks, there results from the weight of their own loose and little coherent mass a more or less perfect stratiform arrangement, which the subsequent infiltration of impurities along these lines of weakness may accentuate.

In no one of these different varieties of cleavage is there any connection with any original stratification, of which there has been found little trace in the rocks. Yet, from causes already indicated, the horizontal partings arising in any one of these ways, are apt to be roughly parallel with the cleavage arising in the other ways, to the upper and lower contacts of the iron-bearing member, and to the true stratification of the slates and quartzites. So, while they are not reliable for working up details of structure, yet, by their horizontal or gently-dipping positions, they roughly conform to the true stratigraphic position of the iron-bearing member, and so are a certain substitute for the true stratification which they have been held to represent.

The reason why each of these varieties of cleavage accords with what should be the stratification has been already stated, but may be recapitulated. In the commonest kind, namely, the horizontal jointing caused by contraction, the first or columnar jointing is necessarily always perpendicular to the true dip of the rocks; and since the second, or horizontal jointing, is at right angles to the first, it accords very nearly with the true dip. In the sheared rocks, where *expansile* tensions have acted, the zones of greatest weakness are found to be generally parallel with the general dip of the member, hence the strain, resisted by the firmer zones above and below, was concentrated into movements in one plane, that is, laterally along the plane of the weaker zone. The schistosity thus developed would be parallel to the zone of weakness, and, in turn, to the dip of the whole formation.

There are several reasons why the zones of greatest weakness must in general be parallel with the iron bearing member as a whole. First, in the formation of the rock, to whatever agency we ascribe it, whether to sedimentary or volcanic forces, whatever zones of special weakness there were must have been generally conformable to the position of the whole sheet. Especially would this be the case if the rock is considered to be of sedimentary origin; for then the successive layers would differ somewhat in material, and among these some would be less able to resist pressure than others. During the processes of change these layers would be apt to remain weaker than their neighbors for a long time.

But in general, these changes would of themselves tend to produce zones differing in kind and degree of metamorphism, parallel to the general position of the member. This is maintained by Irving and Van Hise for the iron-bearing member of the Penokee series of Michigan and Wisconsin,* although here the strata have a steep dip, and the zones have therefore been formed at a large angle to the surface, whence the altering agents have been derived. On the Mesabi, where the strata dip very slightly, and where the surface of the sloping country is at no very great angle with the strata, these zones should be still more clearly differentiated, and as one of these zones must necessarily be weaker than those adjacent, any strain developed in the rock would be relieved by motion of the weaker zone, without much change in the others.

Another important cause of this parallelism is undoubtedly the constant influence of the force of gravity. Even if we suppose that the rock were of uniform resistance throughout, an expansile tension, when it arrived at that importance sufficient for moving the rock, would act in the direction where, other things being equal, it would be least opposed by the forces of gravity. Upward movement would be impossible, because of the great weight of the superimposed rocks; downward movement, on account of the rigidity of the underlying strata; so that the plane in which it must move is that roughly parallel to the upper and lower surfaces. Since these surfaces are themselves slightly inclined, the movement would be aided to some extent by the force of gravity, which might cause a certain slipping of the upper strata on the lower, along this inclined plane. For the whole iron-bearing member, the rigidity of the quartzite and other underlying rocks, and the

*Tenth Ann. Rep. U. S. Geol. Survey, p. 499, Fig. 6.

weight and rigidity of the superimposed strata, operate to confine motions originating in the member to the member itself, in just the same way that, on a smaller scale, within the member itself it has been shown that where a weak zone or plane lies between two rigid zones, motions will be confined to and parallel with this zone or plane.

That sort of cleavage which is developed in pulverulent rocks is almost invariably nearly horizontal, and the fact that it is generally nearly parallel to the other varieties of cleavage depends upon the accident of the nearly horizontal position of the strata. Whatever the attitude of the rocks, the cleavage developed in loose masses by the force of gravity must be very nearly horizontal, or perpendicular to the action of that force. If the strata were inclined, there would probably be a discordance in direction between this cleavage and the other varieties.

THE BANDING AND BEDDING.

Most of the more altered rocks of the iron-bearing member are traversed by bands which are richer in iron than the rest of the rock. These bands are variable in thickness, frequency, regularity, and constancy of direction, but in general they are roughly parallel, and accord in direction with the general attitude of the formation, and with the slaty partings just described. Every detail of the growth of these bands has been described under the microscopic studies of thin sections, but will be briefly summed up here, and some attempt at their explanation made. (See Figs. 2 to 8; also Fig. 11).

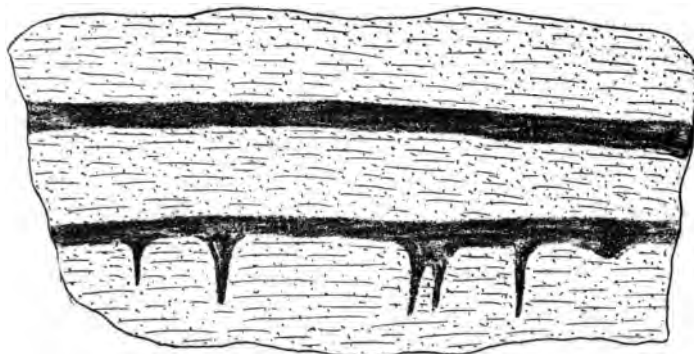


Figure 11,

Sketch of boulder of iron-bearing rock in drift, showing the habit of the bands of iron oxide in the siliceous rock.

It has been invariably observed that during the processes of change in a rock, iron is removed from those portions which are most protected from outside forces, and is precipitated as sesquioxide in whatever places are most subject to oxidizing influences. Sometimes these spots are irregular in shape, and are distributed irregularly through the rock. Thus, when the weak places are small, the ringed or spherical impregnations which form one variety of granules may be formed. When the weak spot is larger, there are formed the shots and blotches of ore which are so common in the iron-bearing rock, and in some limited areas where there is no cracking developed may constitute the only forms resulting from concentration. But where there is a crack or fissure, this is made the zone of concentration. Often the cracks are irregular, in which case the resulting iron bands have no parallelism; but usually the cracks are parallel, and hence the bands bear the same relation. Since it is abundantly proven by observations that these concentrations depend for their existence upon these lines of weakness, we have to account, first, for the cause of the concentration of the iron along the weakest lines; and second, the reason for the general parallelism of these lines.

Under the microscope the steps of the process may often be easily observed, and by this means, traversing the centre of every small band of iron, the crack which was its cause may generally be seen, even when it is not visible in the hand-specimen. Along this crack a narrow band of oxide is precipitated, which gradually grows wider from both sides, although its density decreases as the distance from the original fissure increases. Thus, in the earlier stages of its growth, there is no line of demarkation between the band and the rest of the rock, the band being simply richer in iron and poorer in silica than the central part of the rock, and there may be every stage of gradation between a slender thread of pure oxide in the immediate vicinity of the crack, and nearly pure silica in the central part of the rock. In the next stage, the concentration of the iron and its separation from the silica has gone on still further; the vicinity of the original fissure has become more ferruginous, while the rest of the rock becomes leached to a greater and greater extent; until finally nearly all the iron is in the form of a compact band, which has a sharply marked boundary and contains no silica, and the rest of the rock consists of nearly pure silica, with very little iron. If there are no actual cracks present, there are still potential cracks or at

least spots or zones which are slightly more oxidizable than the rest of the rock, and in these zones the iron will concentrate to a greater or less extent. But so numerous and active are the causes which bring about actual cracks, that the process is really inevitable in a certain stage in the history of the rocks. Specimens at this stage which show in the hand-specimen no banding are under the microscope discovered to be already undergoing the process of concentration. Only those specimens where the iron is confined entirely to the granules can be said to be entirely free from this operation. When there occurs in the interstitial spaces any amount of iron, the process of leaching and concentration has begun. In the Mesabi rocks the result of this concentration is not such perfect banding as in some of the other Lake Superior iron districts; the beautifully striped alternations of quartz and hematite, or "jasper and iron," are a somewhat rare phase, while the initiatory and intermediate phases are the most common. In these phases the bands are not usually perfect, either in shape or in composition; the bands of iron are siliceous and the intervening rock is irony; the shape of the iron portions preserves irregularities which tell much of the history of the growth; and the distance between adjoining bands is variable, amounting sometimes to several feet, sometimes only to a fraction of an inch.

From these inner portions of the rock whence the iron is removed, there finally results the formation of a siliceous cherty or jaspery rock, for as fast as the iron is dissolved out its place is taken by silica. This, with the original silica, which thus appears stable under conditions which dissolve the iron, finally forms nearly the whole mass of the rock. Therefore, we may lay down the rule that in those portions of this rock which are comparatively free from oxidizing agents the iron is more soluble than the silica, so that silica replaces the iron. But in those bands where the iron concentrates along cracks or lines of weakness, the reverse process obtains. In these places the iron which in the interior of the rock was soluble becomes insoluble and is precipitated, and in proportion as the band of iron increases in density, the silica is taken into solution and disappears. So we may lay down the second rule that in those portions of the rock where oxidizing agents have readiest access the silica is more soluble than the iron, so that iron replaces the silica. It is evident, then, that the reversal of the process within the rock to the process along crevices, depends upon the increased access of atmospheric

conditions—the increase of oxygen and the decrease of pressure. From our knowledge of the agents which have brought about these changes, the chemistry of the process may then be assumed to be as follows:

(1) The waters which penetrate down into the crevices of the iron-bearing rock contain, as do all drainage waters, oxygen, carbonic acid, and a certain amount of alkalies and alkaline carbonates.* When this water begins to penetrate into the unoxidized portion of the rock, the oxygen enters into combination with the minerals of the rock, bringing about decomposition and setting free in the process various gases and soluble salts, notably carbonic acid, from the oxidation of certain carbonates, such as siderite; and the alkaline salts, from the decomposition of the silicates. The water which has thus lost its oxygen, along with some of the other materials which it held in solution, passes on, now highly charged with carbonic acid, and the alkalies and alkaline carbonates. Of these substances carbonic acid has the greatest solvent power, its affinity for iron or lime being greater than that of the alkalies for even very finely divided and uncrystallized silica; hence it takes up iron in whatever form it encounters it, whether as the carbonate or the oxide, until the solution becomes saturated. At this stage the water contains iron carbonate, held in solution by carbon dioxide, itself held in solution in water; the excess of carbon dioxide, if there is any; and the alkaline salts, which are unable to dissolve the silica, since the water is already saturated by the action of the carbonic acid upon the iron. The pressure under which the solution is placed in these interstitial spaces permits the solution of a much larger quantity of carbonic acid, and hence of iron, than when it first penetrated from the freer spaces. When this saturated solution, under the laws of circulation, arrives again at any place where there is a larger quantity of oxygen or a release of pressure, the excess of carbon dioxide escapes, and the iron which it held in solution is precipitated as the hydrated sesquioxide. This place is generally a crevice, which may be filled with air, but more generally with waters which are more directly from the surface, and so are in the condition of the saturated solution itself before it penetrated the interstices. By the relief of pressure and the contact with the atmosphere or oxygenated water the solution therefore deposits most of

*See analyses in Geol. Surv. of Missouri, Vol. III., 1892, Mineral Waters of Missouri; also the report on Mineral Waters, Vol. I., Ann. Rep. Arkansas Geo. Surv., 1891.

the iron, and thus becomes again capable of taking new material into solution. Then the alkaline salts are able to dissolve some of the finely divided silica, and carry it away in solution, in place of the iron. Next this solution again penetrates the interstices and again obtains much more carbon dioxide; this, on taking the iron into solution, forces the precipitation of silica, which in its turn replaces the iron. Thus, in its downward progress, the same water may perform the alternating functions an indefinite number of times, till, arriving at the underlying stratum, it has carried silica from the iron-bearing member to form the enlargements of the original grains of sand. This process continues, not only till the silica and the iron are concentrated into separate bands, but, if oxidation continues active, till these bands are themselves concentrated into larger masses.

There is one other cause of the concentration of the iron in such regular shapes, which is doubtless important, although little understood, the "molecular affinity" of iron, which seems stronger than that of silica. By virtue of this the molecules seem to strive after the most compact massing, and after the band is fully formed there is still an action which operates to smooth down the irregularities and make the band more compact and symmetrical. This means that under the attraction of the larger mass of iron other iron will be precipitated from solutions, while at a distance so small theoretically that it cannot be measured, and under the same conditions of oxidation, a smaller mass of iron not only might be unable to bring about precipitation, but might itself be taken into solution.

Having thus explained the concentration of iron along fissures, it only remains to account for the common parallelism of these fissures, which lends to the concentrations a banded arrangement. And this has already been dwelt upon in the discussion of the horizontal jointing and cleavage. For it is the joint and cleavage planes which become the seats of concentration, and give rise to the banded structure. There are less numerous and less conspicuous cracks developed by other causes, which have been observed, but they are irregular and cross each other at angles, instead of being parallel. Irregular contraction and expansion may be assumed to be the usual cause of these, together with irregular cracking under tensions from extraneous causes; in certain cases two sets of parallel lines intersect each other at an angle which makes it probable that they were developed under torsion.

In deposits of ore, and those nearly allied rocks, such as the paint-rocks, where the ore forms the coloring matter, there is developed a very beautiful and perfect banding, in which the bands are so narrow and close together that they may well be called bedded. This is formed under the same general conditions as the coarser banding of the less altered rocks, but it will be given some further notice later.

CHAPTER X.

THE FORMATION AND STRUCTURE OF THE ORE DEPOSITS.

The term *ore-deposit* is relative, and is here applied to those concentrations of iron which are large enough and pure enough to repay mining. As the profit in mining fluctuates with changing conditions, the minimum size of a body of iron oxide which may thus be called an ore-deposit is by no means fixed. Neither is there any essential difference, except in size, between the ore-deposits and the smaller accumulations of iron which are everywhere found in this rock. Between the blotch of concentrated iron which is only a fraction of an inch in diameter, and the mass which is nearly a mile in its greatest diameter, there is every possible gradation, and the explanation of their concentration is in all cases the same: saturated chalybeate waters from the less accessible parts of the rock, have, on coming into a region of freer oxidation, been forced to part with their iron, and have taken into solution some silica; and this has been continued till all the silica was replaced, and the rock was of pure iron oxide. The important thing, therefore, in discussing the ore-deposits, is to explain the causes of their difference from the bands and blotches of ore, *i.e.*, of their greater size. We must first find the cause of the formation of very large areas of weakness and oxidation; and second, the reason for the concentration of a vast quantity of iron and its complete replacement of the original rock.

OCCURRENCE OF ORE-DEPOSITS ON THE MESABI.

The shape of the ore deposits is as variable as their size, but the least diameter of the body is generally the vertical thickness, while by far the greatest development is laterally. Thus the deposits are in general oriented roughly parallel to the general attitude of the Animikie strata. While none of the

large bodies have yet been mined out, so that it is not possible to discover accurately the shape of any one of them, yet in many places test-pitting has been complete enough to give a good idea of the structure. These pits show that there is no sharp boundary line between the ore-body and the barren rock on all sides, into which it runs in the most irregular fashion, but that there is a gradual transition by which the rich ore becomes successively lower in iron and higher in silica, till it is too poor to be mined; and from this to the more decomposed rocks of the oxidation and concentration series. There is no definite wall on any side, neither is there any constant shape. In the largest ore bodies the length of the vertical dimension may sometimes attain some hundreds of feet, while one or both of the nearly horizontal diameters may attain some thousands. Of these horizontal diameters, however, one is apt to greatly exceed the other, so that the generalized shape might be represented by a flattened triaxial prolate ellipsoid. In the actual outline of most of the ore-bodies, however, it would be hard to recognize this fundamental figure.

The greatest clusters of ore-deposits so far known on the Western Mesabi may be included in four rough groups, beginning with that furthest east—the Biwabik group, the Virginia group, the Mountain Iron group, and the Hibbing group. The Biwabik group comprises the mines in the vicinity of the towns of Biwabik and Merritt. The Virginia group comprises all the mines which surround the uplifted region called the Virginia area, and includes the mines near McKinley, from McKinley southwest to the Adams mine, and from the Adams north to and including the great Virginia group itself. The Mountain Iron and the Hibbing groups comprise respectively the ore-deposits in the immediate vicinity of the towns which bear these names. There are other mines, some of them very rich, but in general, aside from these four groups, they are somewhat isolated. The richest of the four groups, the Virginia group, follows, as we have seen, almost continuously the fault-lines which mark the uplift of the Virginia area; and the Biwabik group, which is also of extreme importance, lies in the disturbed and folded region situated immediately east of the Virginia area, whose uplift was probably associated with this disturbance. Unfortunately, the scarcity of outcrops and the covering of drift, necessitating the geologist's contenting himself mainly with material taken from test-pits, hinders the detailed structure being observed here, and still less on the other

and flatter parts of the Mesabi which lie to the west. The Mountain Iron mine lies in a basin, on three sides of which, to the north, east and west, rise ridges of hard rock. The surface of the ore-body is much elongated, its greatest diameter being north and south; thus the greatest axis, if continued, would run through or near the ridge which bounds it to the north. This is a steep bluff of hard "jaspery" rock, mixed with seams of hard iron, which outcrops all the way up the bluff. This outcrop is of special historical interest, since this is the one which was several times visited by explorers in the early days of the Mesabi, and was invariably reported on adversely, while a few yards away, in the valley below, the rich iron deposit comes in many places quite to the surface. The examination of the rock of this bluff, both in the hand-specimen and under the microscope, shows that it has been crushed and brecciated in a most extraordinary manner. (See description of section 97, on page 89).

This does not in any way resemble the straining and brecciation which is common, and has been described as arising from chemical causes originating within the member: the movement has been violent and abrupt. It has almost completely obliterated the original structure of the rock, which is traversed by numerous lines of fracture; and as before noted, these fracture lines are prevailingly arranged into a single well-marked parallel series, indicating a certain single and constant direction of the fracturing force. It thus appears probable that this rock was in the field of a movement of considerable magnitude, some evidence of which has been found in the rocks which constitute the ridges east and west of the ore-body. Since the fracturing forces must have acted in a plane or zone, it seems then probable that that zone lay from the bluff southward through the longest diameter of the ore deposit.

At Hibbing there are no outcrops of the iron-bearing member, and explorations have not been carried on far enough to give any exact idea of the conditions of the rock and the strata in which the ore-deposits lie.

THE EFFECT OF FAULTS UPON THE DEPOSITION OF IRON.

We find, then, that the Virginia group, the Biwabik group, and the Mountain Iron group have all been developed in regions which have been subjected to unusual regional fracturing. When we remember that this fracturing opens up large

areas to oxidizing influences, and that our explanation of the great ore-deposits needs, only the discovery of the cause of these great areas of weakness, in order to be complete, we may well conclude that the development of the ore deposits has been directly dependent upon the regional tensions,—whether the tensions resulted in faulting or folding, or formed only a zone of great weakness, which might easily develop into a fault. The result of the development of such zones is that oxidizing agents are enabled to penetrate every part of them; and under these conditions chalybeate waters deposit their iron, and carry away silica, till the ore-deposit is formed.

Under the areas of special weakness which have thus been formed by extensive disturbance, we may name (1), actual fault-lines, where the fault has resulted in fracturing and movement; (2), incipient fault-lines, where the development of a zone of great weakness under strain has yet not resulted in actual dislocation of the strata; (3), the apices of anticlinal folds and the troughs of synclines, where the strain of folding renders the rock especially weak. To the first of these divisions the Virginia group belongs, while the second appears to be represented by the Mountain Iron; and to the third probably belongs the Biwabik group. Yet in all cases the critical conditions are the same, and so they can be discussed together, for what is true of a fault is for our purposes true, although perhaps in a less degree, other weakened areas

We have now to consider the reason for the carriage of such enormous quantities of iron and their concentration along these lines of weakness; for, although the weakness renders these areas peculiarly subject to ferration, yet there must have been an unusual supply of iron also. This unusual supply of iron will depend wholly upon the supply of the waters which bear this iron, for in any given quantity of waters which penetrate the oxidizable region the supply of iron is somewhat constant, and is near the limit of saturation. We will therefore consider the influence of the development of faults and other zones of weakness upon the supply of waters.

We have already seen that the waters which have accomplished these changes are primarily surface drainage waters, which sink into the porous rocks. In explorations underground, as in wells, mines, test-pits, and the like, it is found that there is at the surface a porous zone in which the fissures are filled mainly with air, except for the downward percolating waters which trickle as near as may be in a vertical direc-

tion. At a certain definite depth, however, the excavation rapidly fills with water, showing that the surface of a considerable body of water has been reached.* From this point downward, the water fills all the crevices in the rock, and its course can no longer be vertical; for the body of ground-water has

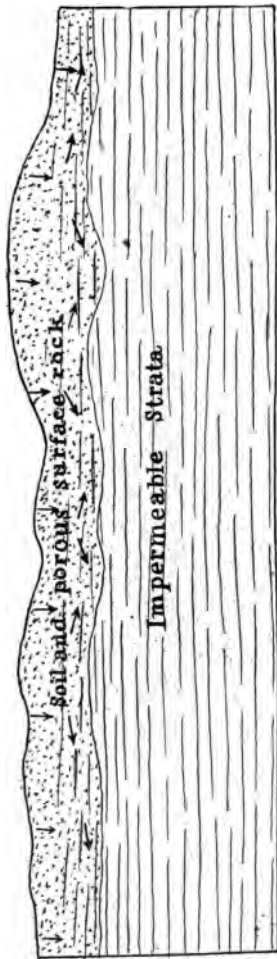


Figure 12.
Section showing the courses of shallow underground waters, in undisturbed regions where the strata are nearly level.

no apparent motion. But where this ground-water level has been determined in several places in the same neighborhood, it is found that the points which represent the ground-water level in the different pits are in a plane which is not horizontal, but is steeply inclined towards the lowest point of the region, or whatever point offers the readiest relief to the hydrostatic pressure. (See Fig. 12). Down this plane, therefore, the whole body of surface waters slowly moves, to once more reach the surface at a lower point, as springs.

"The total difference," says Posepny,† "in altitude between the water-level and the surface outlet is always the controlling factor.

"When these two controlling levels are artificially changed, as often happens in mining, the law still operates. In sinking a shaft through permeable ground, it is of course necessary to lift continuously the ground-water. The water-level thus acquires an inclination towards the shaft, which may thus receive not only the flow of the im-

mediate vicinity but even also that of neighboring valley-systems. A shaft imparts to the previously plane water-level a depression, giving it the form of an inverted conoid with parabolic generatrix. An adit produces a prismatic depression in the water-level, and so on for other excavations. On the other hand, a bore-hole, from which the water is not removed, does not affect the water-level."

*See Posepny, Trans. Am. Inst. Min. Eng., August, 1893. The Genesis of Ore Deposits, p. 17, from which certain of these statements are adapted.

†Op. cit. p. 17.

The opening of any great zone of weakness such as that which attends a fault, would bring about an important change in the circulation of the surface waters. The waters in the vicinity would find their easiest passage into this fissure. The plane which represented the water-level before the formation

of the fissure would be divided into two planes, each sloping towards the fissure, and the course of these two currents would be quite different from the course of the drainage before the formation of the fault. In other words, a prismatic depression of the water-level, like that produced artificially by anadit, but on a much grander scale, would be produced; and there would be deflected into this opening all the drainage waters of a large surrounding region, the size of this area depending upon the size of the fissure. The development of a vertical zone of weakness, which yet did not develop into a fault, would constitute a region permeable by water, and would have the same effect upon the drainage, though in a less degree. If the fissure should be slight, and tight at the bottom, it would soon become filled with water, the flow into it would cease, and the water-level

would be restored to its old plane; but almost all ways this fissure communicates with another lower down, or with another porous stratum, and thus the circulation established becomes permanent. Especially is this true in the case of faults and similar dislocations, which extend to great depth with little diminution of importance, and somewhere in their downward course almost inevitably meet with some passage-way for the waters to reach the surface again. (See Fig. 13).

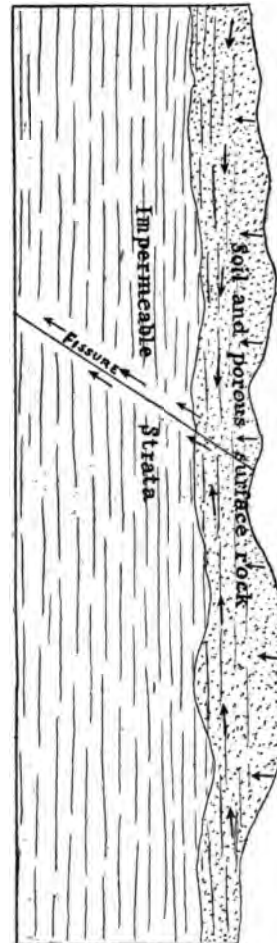


Figure 13.

Compare Figure 12. This shows the deflection of the shallow underground circulation by the opening of a fissure.

Faults such as those which have attended the uplift of the Virginia area would weaken the rocks through which they pass for a considerable distance from the actual line or lines of dislocation. The dimensions of this area, and the intensity of the straining, would depend upon the qualities of the rocks which were thus operated upon. Thus of the three most important members on the Mesabi—the upper slate member, the iron-bearing member and the quartzite member—the quartzite would undergo least comminution and would be at the end of the process least porous of any; for from its rigid and brittle nature, the strains would be relieved by sharp fractures, while the interstitial spaces would remain as impenetrable as ever. Next in point of strength would come the slates, where there would be developed a considerable degree of porosity. Weakest of all, in general, would be the iron-bearing member, in its more ordinary phases; for here the general decomposition would already have rendered the rock partially disintegrated and porous. All the materials, moreover, are very finely divided, and the application of the strain would produce in this member a vastly larger area of weakness than in the others, but especially than in the underlying quartzite. The areas of general interstitial weakness, therefore, which result from a fault like that at Virginia, may be represented diagrammatically by figure 14.

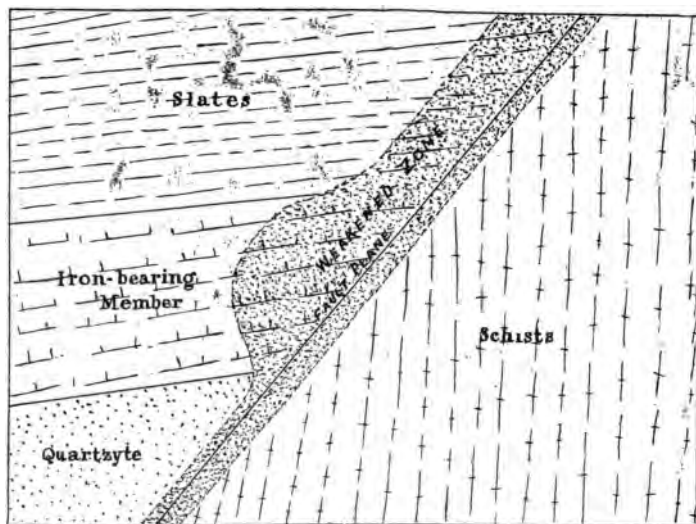


Figure 14.

Theoretical section across the Fault near Virginia, showing the relative size of the areas of weakness developed in the different strata by the faulting movement.

Where there is no fracturing, the quartzite which lies below the iron-bearing member has very few joint-planes or other fissures, and so forms a stratum practically impermeable to water. On the other hand, the iron-bearing member as a whole is porous, and affords the easiest passage for all surface waters. Roughly speaking, therefore, the thickness of surface waters is the distance between the ground-water level and the top of the quartzite. The quartzite forms the water shed along which, and through the iron-bearing rocks, the drainage waters pass to the point of least pressure. The waters which are deflected into the newly-formed fissure will then, in the first place, be very highly charged with iron, since their passage has been entirely through the iron rocks; in the second place, nearly all will emerge into the weakened area at that point where the fault crosses the bottom of the iron-bearing member. At this point the chalybeate waters will deposit their iron, take up silica, and pass on in the same direction, along the surface of the still only partially penetrable quartzite, till, with the approach to the actual plane of dislocation, the fracturing of the quartzite develops sufficiently to allow the waters to penetrate downward. What little iron they still contain may be deposited in the very topmost parts of the quartzite, and silica taken up in return; but on account of the coarsely crystalline nature of the silica the process of replacement is extremely slow, as compared with that of the cryptocrystalline or chalcedonic silica of the iron-bearing member; so that it has never been found that such replacement has any commercial importance; moreover, the supply of iron in the waters by the time that they reach the quartzite is so slight that it is soon exhausted, and the silica-bearing waters go on downward, depositing their silica if opportunity offers, especially as the enlargements of the original sand-grains, or retaining it and re-appearing at the surface as siliceous springs.

The first deposition of iron, therefore, will be a thin film lying directly upon the quartzite, beginning in that part which is furthest from the actual plane of dislocation, and where the oxidation is slight, in a very poor seam. This gradually increases till at the first point of free oxidation it becomes richest, for here most of the iron is deposited. From this point to the chief fault-plane it becomes successively poorer, for, although the oxidation gradually increases, yet the quantity of iron to be precipitated diminishes with greater rapidity. At the same time, what iron, silica, and other substances

have been deposited in the fault-fractures or even the interstices of the strained rock (whether it be of the iron-bearing member, the quartzite, or any one of the formations which may exist further down, along the course of the underground waters), diminish the volume of these passages, although to so slight a degree that it appears infinitesimal. But this principle is extremely important, for every particle which is deposited thus along the water-ways, in diminishing their size, diminishes the quantity of water which may escape within a given time. The quantity of drainage water which may escape through this fissure being thus diminished, the prismatic depression in the original plane of drainage becomes less important, for the line along the fault where converge the two new planes of ground-water surface, which follows the drainage created by the dislocation, rises slightly and the plane angle becomes slightly more obtuse. From this decrease in the inclination of the ground-water level planes it follows that the area drained by them diminishes slightly, and that on the borders of the area a small outer rim returns to the drainage which it followed before the deflection by the formation of the fracture.

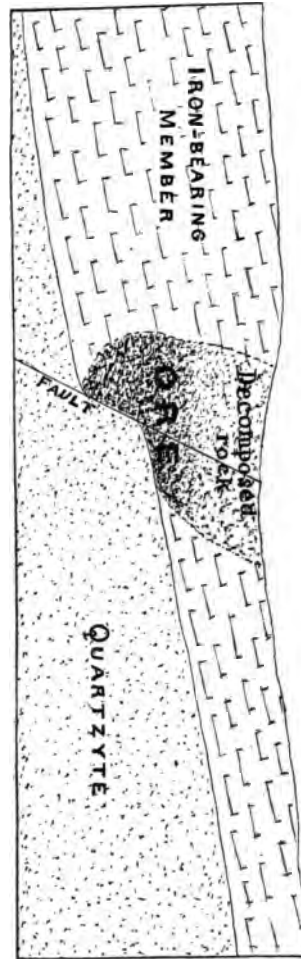
In the next deposited layer, the ground-water level will be somewhat higher than at the first, hence a thin layer which was not affected at first becomes oxidized. The outline of this new superimposed layer is convex, like the first, but the circle of which it is an arc is a much larger one than that of the first layer. This arises from the fact that the ground-water level has been heightened almost imperceptibly, while the amount of iron in the waters is as great as before; thus when the solutions reach the first plane of free oxidation, where was formed the thickest parts of our theoretical first layer, it does not part with so much of its iron as did the first solution. For the greater part of it passes through the same rock as did the first, where the previous deposition has diminished the capability of replacement; moreover, the layer of unaffected rock at the top, whose thickness is represented by the difference in the ground-water level of the first and of the second solutions, is extremely thin. Thus the waters pass on, and deposit their maximum amount of iron a little further on than before. These layers are repeated an infinite number of times, till the richest part of the layers is deposited at the plane of greatest dislocation. We have now arrived at the stage when the accumulations are important enough to allow their observation

in the field. We have, at the bottom of the iron-bearing member, a thin seam of iron, of nearly constant thickness, resting upon the basal quartzite and extending as far laterally as does the zone of weakness of the iron-bearing member, and with a general tendency to be richest in the zones of greatest weakness, and poorer as the distance from those zones increases.

The subsequent history of the formation of ore-deposits along these zones of weakness is only a repetition of these first steps. The chalybeate drainage waters, by their continual deposition of iron and their leaching of silica, keep making the lower layers more and more pure in iron, till the process is completed; and at the same time by their gradual filling of fissures and interstices by iron and silica, increasing the height of the ground-water level, so that continually a higher layer of the weak zone comes under the influence of active ferration. Progressively with this process, the depression in the original plane of drainage becomes less and less, and the

underground area which sends its drainage to the weak zone becomes correspondingly smaller. In the end, there must result the replacement of nearly all of the silica of the weak zone of the original iron-bearing member by iron. This means an immense ore-deposit. The original fissure will also have been chiefly or wholly filled, and the drainage gradually restored to the single plane which it occupied before the catastrophe which induced the formation of the zone of weakness. It is to be remarked, however, that that portion of the rocks

Figure 15.
Theoretical section to show formation of ore-deposits along a fault-plane. Note relation of topography to the ore-deposits and the cause.



which lies above the restored ground-water level may never become completely ferrated, and, indeed, this is the normal case. It is true that in most ore-deposits at the present day the ore lies at the surface, directly below the glacial drift; but it is probable that in nearly every case there once existed above it a "capping" of less altered rock, which, together with some of the ore, has been long since removed by erosion. There are moreover, several well-authenticated cases of siliceous cappings of no great thickness overlying deposits of good ore, and these must be explained in this way. (See Figs. 15 and 16).

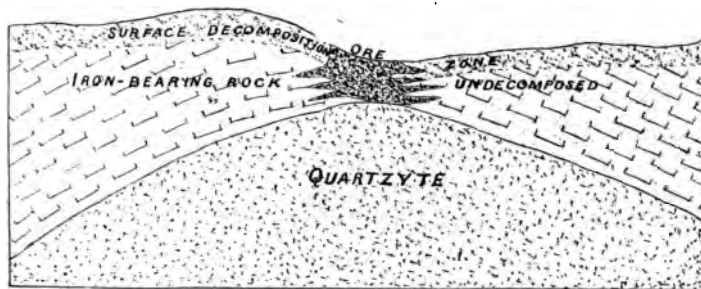


Figure 16.

Theoretical section, showing formation of ore-deposits in the weakened zone, along the axis of an anticlinal fold.

Evidence of the gradual filling of these spaces, which we may properly call ore-basins, has already been given in the discussion of thin sections, where it is found that a rock which has been leached of its iron (in this case generally without replacement by silica) and thus reduced to a porous or semi-pulverulent state, was afterwards, by the rise of the level of the ferrating waters, saturated with iron, and changed into ore. This has been particularly well observed in the siliceous rocks which form the rim of the Mountain Iron and Virginia basins. But in nearly every test-pit the transition of paint-rock to ore illustrates this. The paint-rock, as already described, is originally only the leached and decomposed residual product of the decay of the primitive iron-bearing rock; but this has become subsequently stained with iron. As we go down, the richness in iron increases, till streaks of material which may be classed as lean ore are found, and finally the gradation leads to the actual ore-deposit. The paint-rock which thus by saturation becomes transformed into ore had first contributed all of its iron to the lower levels of the ore-deposit, but with the filling up of the basin it has itself become again thoroughly ferrated.

Influence of Dikes on Ore-Deposits.

To recapitulate, the cause of the largest ore-deposits on the Mesabi is believed to depend upon the development of regional fractures or lines of weakness. So far as has been observed, there are no other points of difference between the rocks which have formed the ore-bodies and the rocks in the other parts of the member. Irving and Van Hise* have shown for the Penoque region that the ore-deposits are associated with underlying dikes, which are so arranged with the basal quartzite as to form basins in which the ore is believed to have been concentrated; but on the whole Western Mesabi, so far as is known, there has been found no trace of any dike or other igneous rock in the Animikie. If such dikes existed, it is probable that near them would be formed ore-deposits. If the dikes formed troughs with themselves or with an impenetrable stratum like the basal quartzite, the ore bodies might occur in the manner described in Michigan and Wisconsin.

But even if no such troughs were formed ore might accumulate near the dikes, partly on account of the less easily penetrable stratum which they would form, but chiefly on account of the weakening of the iron-bearing rock under the shearing which accompanied the introduction of the dike. We should then have this succession: First the harder, unsheared rock of the iron-bearing member; next the sheared and oxygenated zone lying on the upper side of the dike, and having its maximum of weakness not far from the dike itself; next the hard, nearly impermeable igneous rock; below this another strained and oxygenated zone; and finally the hard unstrained, siliceous iron-bearing rock, or the basal quartzite. When these layers outcrop at the surface, drainage waters find two porous layers, lying on either side of the impermeable dike; and there are formed two chief underground channels, the one above, with its water resting upon the dike; and the other below, with its water resting upon the lower hard stratum of iron-bearing rock, or upon the quartzite, according to the location and direction of the dike; and both bodies of water have about the same course. This circulation would begin immediately after the intrusion of the dike, and the chalybeate waters would proceed to replace the weakened siliceous rock through which they passed and to deposit iron. In both channels those solutions which were most highly charged with iron would sink by

*Tenth Ann. Rep. U. S. Geol. Survey, pp. 409-422; also plates XXXVI and XXXVII.

reason of their greater weight, and would lie closest the foot-wall. In the upper porous stratum this lowest part would also be the zone of greatest weakness, thus allowing the passage of a greater amount of waters within a given time than any other part of the stratum; this therefore, is also the zone of easiest replacement, so that the same quantity of a solution of given strength will replace more silica here within a given time than in any other part of the stratum. So the first deposition of iron will be upon the foot-wall of dike rock, and from this the ore-body will grow upward. In the lower channel the conditions are somewhat different. Here, again, the richest solutions tend to concentrate at the bottom; but, at the same time the zone of greatest weakness, of freest passage and most rapid replacement, is near the top, in the vicinity of the dike. So here the results of the first stages of deposition will be distributed more uniformly, partly in the lower, partly in the higher zones, and the rate of growth in the different zones will remain more nearly uniform till the process of replacement is quite completed. If a section should be made through the upper and the lower permeable strata, before the process of replacement is completed, there would probably be encountered at the upper layers of the upper permeable stratum, a lean, little-ferrated rock; at the lower layers of the same stratum, resting upon the dike, a deposit of rich ore; below the dike, a somewhat ferrated rock of lean siliceous ore, which should have some uniformity in all its layers, even down to its foot-wall. If, however, the section should be made in a case where the ferration was complete, there would be found, in place of the original permeable strata, deposits of ore both above and below the dike, that below being usually poorer and sometimes nearly absent, depending upon the relative permeability of the underlying rock.* It will be seen that this class of ore-deposits, which are not known on the Mesabi, are still included in the general statement made for the Mesabi, that "the cause of the largest ore-deposits is believed to depend upon the development of regional fractures or lines of weakness."

On the Mesabi, however, the cause of the regional fractures is folding and faulting, and not the intrusion of dikes. The date of this regional disturbance is very ancient, for the time necessary for the accumulation of these great ore-deposits is

*C. B. Van Hise, *Iron Ores of the Marquette District of Michigan*. Am. Journ. Sci. Vol. XLIII, February, 1892, p. 123. Figures showing occurrences of ore in the Marquette region. In Figure 1 deposits of ore are seen on both sides of a vertical dike. These deposits are about equal in size, and both rest on chert.

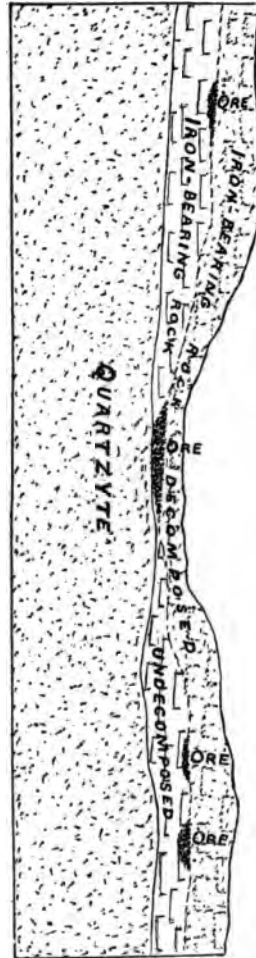
immense; so they are all hypothetically assigned to the same age as the greatest of them, the Virginia uplift, and this, with the tilting and corrugation of the Animikie strata, has been assigned to the Keweenaw.

Besides this chief cause, there are others which sometimes give rise to regions of especial weakness, which then become in time ore-bodies. Ore-bodies developed in this way are smaller, but they are often of economic value. First may be mentioned the production of strain originating in the iron-bearing member, and caused by the chemical changes in it. These strains produce often faulting, brecciation, folding, or, most often, simply the development of an area of greater weakness than the surrounding rock. The effect of these upon the formation of ore-deposits is to be explained in the same way as the effect of the regional catastrophes, since they differ only in being of much less magnitude, on account of their being produced by a less powerful force. To this cause probably owe their origin many of the smaller and less important ore-bodies. Still a third class, which in some cases becomes of

some importance, has no connection with any dislocation of the rock; the permeable stratum lies at the surface, and has been rendered porous by the weathering of surface agents, with no apparent auxiliary force. At the bottom of this weathered stratum the hard, little-decomposed rock forms a foot-wall, upon which, under favorable conditions, the building of a deposit of ore commences, which, as in other cases, grows upward by successive additions. (See Fig. 17). The

Section showing formation of small ore-bodies along the boundary between the decomposed iron-bearing rock at the surface and the little altered rock lower down. Note the relation of the topography to the ore-deposits, and the cause.

Figure 17.



process is practically the same as before. Those waters which have traveled for a long distance laterally along the foot-wall of hard rock become saturated with iron. They are being continually joined by others which come more directly from the surface, and so are more highly oxygenated. The first effect of the meeting of such solutions would be that the oxygen would precipitate from the saturated solution a certain quantity of its iron as the oxide; and in this way the ore was formed. After the oxygen, however, has been separated from the waters by the precipitation of the oxide, these waters, by reason of their dilution, are enabled to take into solution a renewed amount of iron, which they carry on, all the time depositing a certain amount in concentrated form and taking fresh material into solution from its disseminated state. We are best able to identify this third class where there is a thin covering of the upper slate member, thus making it certain that we have in the upper permeable stratum of the iron-bearing member a zone which represents the original surface; and cannot possibly be a weak zone from above which the harder rocks have been removed by erosion produced within the member by some mechanical force. An example of this has already been mentioned, the drill-hole near McKinley, of which the record, kindly supplied by Mr. H. V. Winchell, is as follows: (See Fig. 10).

Swamp and glacial drift material.....	51 feet.
Slates.....	58 "
Porous iron-bearing rock (somewhat leached).....	15 "
Hard hematite.....	4 "
Hard, impermeable iron-bearing rock passed through to the thickness of 39 feet, and then the boring was stopped.	

A pit sunk by Longyear through the slates in the basin of Embarras lake encountered in the upper horizon of the iron-bearing member below, the same phenomenon of lean ore.

When by unequal surface decay there has been formed a depression in the foot-wall of less altered rock, this depression will be made the receptacle for a larger and more permanent body of water than other parts of the surface. Hence deposition and replacement will go on here more rapidly, and in time this ore-basin will be filled. As in the nature of the rocks and of the decomposing processes, the conditions are so varying that such depressions must constantly occur, they may be often of such extent as to give rise to ore-bodies of economic importance.

RECEIVED

STRUCTURAL PECULIARITIES OF ORE DEPOSITS.

The chief structural features of ore deposits, which are not shared by the other rocks of the iron-bearing member, are the often well developed bedded or laminated appearance, and the frequent contortions and faultings of these layers.

It is hardly necessary to reiterate that the laminated structure has nothing to do with stratification. This is quite sufficiently proven when it is remembered that the ore-deposits represent the extreme result of all the decomposing and reorganizing influences which have affected the iron-bearing rock, and so, if any trace of the original structure remained, it would be much fainter than in the less altered rocks. But as a matter of fact, there is in the freshest rocks no trace of any bedding, or even of any parallel structure; with the progression of the decomposition and rearrangement, however, a rough banded structure begins to be present, and with the change in the rocks and the obliteration of the original structure, the bands grow more numerous and more perfect. The growth and cause of these bands has already been ascertained; and in the extreme of the normal process, which is represented by the jasper and iron, the alternating bands of iron and silica are often very perfect and beautiful. But in the extreme of the oxidation and concentration process, which is represented by the ore-bodies, the alteration has gone further yet, and as a result the laminæ are still closer together and more regular. The cause of their formation is precisely the same as for the coarser bands. In the more altered rocks, where the carbonate has all been oxidized, it has been shown that the multiplication of the horizontal jointing brings the joint-planes so close together that the result resembles slaty cleavage. As the free oxidation which produces this structure is also the essential condition for the formation of ore-deposits, it happens that this much-jointed rock and the ore are found often very closely associated; as, for example, at Virginia, at the Ohio mine. When this rock is replaced, the first bands of iron are formed along the joint-planes, as are all other bands in other phases of the rock; and the rock lying between the joint-planes is not replaced till later. Thus the different ages and conditions of formation are preserved in the completely ferrated rock, and form the laminæ of the ore. These laminæ are marked, at the present time, by alternations of lighter and darker bands, of which the former contain less iron and more

combined water than the latter. The darker layers, in this case, may be asumed to have been the first formed along the joint-planes; and the lighter ones, the spaces of rock between them, which was first partially leached and then ferrated.

The laminated structure of ore-bodies is a very common feature, both in sedimentary and igneous rocks. Judd* has described many such cases in England, in ore-bodies which have been formed by the replacement of limestone. We quote briefly:

The accumulation of oxide of iron, in laminae roughly parallel with the bedding and jointing of the rock, is by no means peculiar to the Northamptonshire ore. * * * * From a study of a large number of these cases, we are led to the conclusion that in all of them the penetration of atmospheric water is the cause. * * * *

He then explains the chemistry of the process in the same way that we have already explained the formation of the coarser bands in the less altered rock.

Posepny,† in the discussion of "Deposits in Crystalline Schists and Eruptive Rocks," makes the following remark:

Many indications, available in the distinctively sedimentary rocks as guides in the determination of the relative age of their ore-deposits, are here wanting. The bedding becomes more and more obscure, and is no longer distinguishable from the cleavage. Many of the ore-deposits in these rocks have also become in whole or in part crystalline, adjusting themselves to the prevailing stratification or cleavage, so that most of them present a bed-like structure and form. Whoever believes in the contemporaneous origin of ores with the rocks will not trouble himself here with genetic speculations, but will see in these deposits simply "ore-beds," according to the old classifications.

In this connection he cites the case of the zinc-blende deposit of Ammeberg,‡ in Sweden, a case of replacement of the original rock:

In a winding line * * * occur steeply dipping beds of gneiss in granulite. * * * At certain points they show very beautiful close folds. At first glance they seem to be genuine intercalated beds of the same age as the rocks. The ores, however, do not continue along the whole line, but form separate lenses, up to 15 meters (49 feet) thick, which show a distinct stratification, consisting in layers of fine-grained to amorphous material resembling *hällflinta*, alternating with the coarser granulite. * * * The entrance of the ore into the coarsely crystalline layers seems to have been attended by an enlargement of their volume, which resulted in their breaking through the dense layers.

*The Geology of Rutland, etc., by J. W. Judd, p. 130. "Mode of Formation of the Northamptonshire Iron Ore."

†The Genesis of Ore Deposits, p. 126.

‡Ibid., p. 129.

The same explanation is required for some parts of the bed, in which, between the two plane surfaces of two fine-grained, barren strata, ore occurs in highly folded and contorted layers. This folding is due by no means to an exterior mechanical energy, but to interior chemical forces.
* * * *

This Ammeberg deposit, then, though so distinctively bedded, is by no means of primitive origin. * * * *

The contortions of the laminae in the ore deposits is often very great, and there may also result faults and folds. The fact that these faults and folds are confined to the ore body and do not extend to the less altered rock which surrounds it; moreover, and found nowhere except in the ore bodies, shows that the disturbance has taken place since the concentration of the ore. It also shows that the force which led to the folding has probably originated within the ore body itself. These contortions are particularly abrupt where the ore abuts against a hard unyielding wall of less altered rock. A good case of this was seen at the Hale mine, near Merritt, where the ore rests on its northern side directly upon the hard schist of the Kewatin. Here there have been developed much broken contortions, and the general position of the layers has been changed so that they dip to the south about forty-five degrees. The nature of these contortions makes it clear that the laminae of ore have been pushed laterally against the unyielding wall of schist, and that the folds are the result of this compression. The force which caused the motion, therefore, was confined to the ore body, and did not affect the schist, and so it could not have been due to any regional disturbance. In other mines, such as the Ohio at Virginia, the same thing was noted, and here, as at the Hale, the contorted layers were near a bounding wall of hard rock.

It seems to be the case that the contortions are uniformly greater and the laminae more pronounced, near the surface, while with increasing depth the ore becomes uniformly and evenly bedded, the layers running in a nearly horizontal direction. With this diminution of the disturbance there is also associated a change in the nature of the ore; at the top there is apt to be, as seen in many of the mines of the Biwabik group,* a zone of the highly hydrated yellow limonite or göthite. While this is a surface deposit, it is often of considerable thickness. The ore at the Hale mine of this character. Going downward, the ore changes, till there is reached the granular "blue hematite," which is the best and purest ore. The change is primarily a

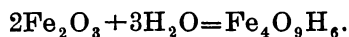
*Twentieth Ann. Rep. Minn. Geol. and Nat. Hist. Survey, p. 136, and plate I.

decrease in hydration. We thus find that the steep folding is in the first place confined to the ore bodies, and, in the second place, chiefly to the hydrated portions of those ore bodies. We may now easily understand the causes of the force which has produced this folding.

We may assume that the hydration of the upper horizons was subsequent to the formation of the ore-body. By the processes of replacement, there should have been originally no great difference in the condition of the ore deposited in different horizons. This original state was probably a somewhat hydrated sesquioxide. After the concentration of the iron in this form, the force of the crystallizing motive led to the dehydration of this oxide and the clustering of the earthy mass into crystalline grains of hematite, thus producing the "blue granular" ore. This hematite is considered the best, not only on account of its comparative freedom from combined water, but because the process of crystallization has somewhat purified the ore by the exclusion of many of the impurities, such as phosphorus. The ore, by its crystallization, is rendered very porous, and so the waters act with increased energy, and have operated to carry off those impurities which were not taken up by the crystallizing iron. So the blue hematite is ordinarily a high-grade bessemer ore.

When, however, by the process of erosion, it arrives that the overlying horizons are stripped off, and this crystalline hematite is brought to the surface, the great quantities of surface waters begin to affect the upper layers of the hematite and to change it into hydrated varieties. Among these limonite and goethite may be named, but there appears to be very many stages of hydration, as indicated by the gradually changing color of the ore on proceeding from the bright yellow limonite to the blue-black granular hematite.

The change from the anhydrous to the hydrous variety involves an increase in volume, in the same manner as does the change from the oxide to the carbonate, before described. If we take the change from anhydrous hematite to limonite as a typical example, the reaction which takes place may be expressed as follows:



By the addition of the combined water there is an increase in weight from any given quantity of hematite to the quantity of limonite thence derived of about 14.5 per cent. Since the

density of limonite is somewhat less than that of hematite, the increase of volume would be somewhat greater. As, in this case, the rock consists entirely of ore, this must be the degree of expansion of the whole rock-mass attendant upon its complete hydration; although the amount would not be so great where the hydration was only partial. Some of this expansion would be relieved in the interstitial spaces, and the result would be to make the ore somewhat earthy; the rest has caused the crumbling and folding of the highly hydrated horizons.

With the reduction of the iron to the earthy and hydrated state, it becomes a more active absorbent of impurities, and one of these, phosphoric acid, which is contained in very small quantities in nearly all waters, is especially injurious to the commercial value of the ore, and brings it in many cases out of the bessemer limit.*

THE EASTERN MESABI.

What has been hitherto written has been chiefly concerning the Western Mesabi. It may be now well to inquire the cause of the peculiarities of the iron-bearing member upon the Eastern Mesabi, especially the reason for its comparative unproductiveness of large bodies of concentrated ore. In this connection it is necessary to consider the attitude of the Animikie strata, and the cause, for, although this topic properly concerns the whole Animikie series, yet its application is here of the greatest importance. It has been previously suggested that the tilting of the strata was probably due to the weight of the Keweenaw lavas, as is shown by the inclination of the strata towards these massive igneous rocks, the increase of disturbance as these areas are approached, and the comparative freedom from any action in the region most remote. Upon the Eastern Mesabi the Animikie strata are pierced and intermingled with the northern border of the Keweenaw rocks, so that their normal attitude is often much disturbed, and the true stratigraphy rendered very puzzling. As we go away from here, both to the south west along the Western Mesabi, and to the north-east along the International Boundary division, the disturbance grows progressively less. With this change there is associated another, in the iron-bearing member, which is best shown going south-west along the Western Mesabi; for in the opposite direction the iron-bearing member is not well-developed. This is a progressive decrease of the

*Twentieth Ann. Rep. Minnesota Geol. Survey, p. 137.

crystalline state of the silica, and the magnetitic state of the iron. Nearly all the iron of the Eastern Mesabi is magnetic, whether concentrated into bands or small ore-bodies, or disseminated through the rock in shots or grains. It is furthermore associated with hard, crystalline silica. But as we get out of the immediate vicinity of the Keweenawan rocks, the quantity of magnetite rapidly decreases, although it is found sparingly throughout the whole extent of the Western Mesabi even as far as Pokegama falls. But, on the whole, nearly all the iron on the Western Mesabi is hematitic or limonitic, and nearly all on the Eastern Mesabi is magnetic. It is probable, therefore, that this change in the nature of the rocks is connected with the decrease in disturbance of the strata, and that both were accomplished at the same time by the advent of the Keweenawan rocks. These views were first expressed by Mr. Horace V. Winchell.* The magnetite in the Eastern Mesabi rocks is scattered in such a way as to show that it is the result of a concentration like that observed going on upon the Western Mesabi; but in the latter place it seems probable that the iron is rarely or never deposited as magnetite in such concentrated forms, but always as the earthy, more or less hydrated sesquioxide. On the Eastern Mesabi, therefore, it must be that this iron was originally in the state of the sesquioxide, and that at the Keweenawan time it became magnetic. We may then account for this magnetization in two ways. First, the direct heat of the igneous rocks. This would change to the crystalline and magnetic condition the semi-concentrated silica and iron for a considerable zone, perhaps for several miles, for the influence of a very slight degree of heat, if long continued, is quite sufficient to produce the magnetization of hematite. Second, and most important, the indirect application of heat through the disturbances which the Keweenawan rocks produced in the Animikie strata. Near the centre of disturbance, the internal heat developed by these movements must have been sufficient to completely magnetize the iron; while with the increasing distance the heat, and therefore the magnetizing influence diminished. But as there was some disturbance felt along the whole length of the Mesabi, so we find some small magnetizing action quite to the end of the range.

The effect of this contact and regional metamorphism would be to render comparatively stable the minerals of the iron-bearing rock, by subjecting them to a rapid crystallizing

*Twentieth Ann. Rept. Minn., Geol. and Nat. Hist. Survey, pp. 120-121, and pp. 134-136.

action. The result would be a good deal like what has been indicated as the final stage of the normal process of decomposition and rearrangement, under ordinary atmospheric influences: the molecules of iron and of silica, from their loosely united state in the earthy hematite and the cryptocrystalline silica, became firmly bound together by the crystallizing force, and thus become comparatively stable and resistant to the degrading effects of atmospheric agents. By this violent method the process of decomposition and concentration was brought to a sudden close; the attainment of stability was accomplished suddenly, and without the extreme concentration that was necessary under ordinary atmospheric conditions alone. We may believe, therefore, that since Keweenawan time the changes in the rocks of the Eastern Mesabi, and the oxidation and concentration of iron, have not been great. But upon the little-affected Western Mesabi, the processes of concentration, which were already well advanced, suffered only a slight check, and continued up to the present day. This is probably the reason for the poverty in large ore-deposits of the Eastern Mesabi. The ore there, roughly speaking, represents the concentration as accomplished up to the Keweenawan epoch, while that on the western part of the range represents the uninterrupted result of the concentrating forces down to the present time.

ORES IN THE CRETACEOUS OF THE WESTERN MESABI.

The Cretaceous occurs in small residual patches on the Western Mesabi, as has been described. Its most common form of occurrence is as a conglomerate which is generally almost entirely made up of fragments from the iron-bearing member, which in each case it has been found overlying. This conglomerate has been found, first, in the southwest quarter of section 20, T. 58-19, where it has been positively identified* because of the associated fossil-bearing shale. It has also been found in the southeast of the northeast quarter of section 6, T. 58-17. Finally, a conglomerate which resembles that of the other two localities, and belongs probably to the same horizon, is found in the northeast of the northeast of section 10, T. 58-18. The material of which these conglomerates are composed, and which has been derived from the iron-bearing rocks, is found here in all stages of the transitional changes. Not only

*Horace V. Winchell, *Am. Geol.*, October, 1893. Note on Cretaceous in Northern Minnesota, p. 221.

the fragments, but the cement between them is thus composed, and many things go to show that these materials have undergone much chemical change since the time they were broken from their original beds and incorporated in the Cretaceous conglomerates. One of the commonest of these is the complete and almost general ferration, in many parts. The fragments and cement alike, have been penetrated by the iron oxide, and the conglomerate has thus been transformed into a hard mass of lean iron ore, breaking with a conchoidal fracture. This ore is gray and often partly magnetic, but is distinguished from the other ores of the range by its large content of sulphur, which, in the form of pyrites, usually gives a yellow tinge to the mass. In other specimens there has been a leaching without much ferration, and as a result, the whole conglomerate is made up of a mass of soft decomposition powder or hardened paint-rock; in this case the fragments are often not so completely changed as the more finely divided cement, and contain, in the centre, hard siliceous residual cores which resemble some of the stained cherty or finely siliceous varieties of the rock as we find them in place. In the conglomerate in section 6, T. 58-17, some of the larger pebbles are even more plain in their story. Here was noted in the conglomerate, a boulder eight or ten inches in diameter, which on the outside seemed to be a light red paint-rock. On breaking it open, it was found that the centre was composed of the hard, brown, and siliceous conchoidal-fractured phase, which is so common in the iron-bearing member.

But it had gradually decomposed till it formed a nearly white powder, in a zone which was parallel to the periphery, and this in turn had at the very outside been stained to form the paint-rock. Smaller pebbles had been more completely changed, for the zone of decomposition had taken up more of their volume; and one, which was smooth in outline and subangular in shape, suggesting considerable attrition before being deposited, was composed entirely of the soft white pulverulent rock, and could be broken with the fingers or cut with a knife. This was about an inch and a half in diameter, and was plucked out from the conglomeratic mass in which it was imbedded. These fragments could never have retained their integrity in the midst of the rolling which their shape indicates, had they been at the time of their incorporation of the same pulverulent nature as now; and in the larger fragment, moreover, the zonal relation of the decomposition products, parallel to the periphery, shows

that *all* of this decomposition took place after the fragment had acquired its present shape. These rocks, then, represent the action of the oxidation and concentration process, accomplished, for the most part, since the Cretaceous period; while the highly ferrated conglomerates represent the iron which has thus been leached from these decomposed and now pulverulent rocks. The great quantity of sulphur in these ores is accounted for by the organic matter in these beds, which produced abundant sulphuric acid. In the presence of this the iron was precipitated, and as a result, a large part of it is in the form of sulphide. None of this ferrated conglomerate contains enough iron to make it of economic value in this region; and even if this were the case, the amount of sulphur renders it useless.

There is no doubt, however, that much of the iron which is found in these conglomerates was already concentrated when taken into the beds, and has since undergone no great change. In the conglomerate in section 10, T. 58-18, a pebble of this iron, about four inches in diameter, was found, which exhibits great pyritization on the periphery. But this decreases inwardly till in about one-third of the diameter the yellow tinge fades away. The ferration of this pebble is equal and complete throughout. In this case the ferration and the pyritization have probably not been contemporaneous; but the pyritization was subsequent to the completion of the former. Moreover, the zonal pyritization shows that the process occurred after the pebble had assumed its present form, *i. e.*, after its incorporation into the conglomerate; while of the ferration there is no such evidence. It is probable, therefore, that most of the ferration of this pebble was accomplished before Cretaceous time.

So, in this conglomerate, there are both pre-Cretaceous and post-Cretaceous iron; and the proportion of the two is not certain. But when we consider that even where all the evident changes have been post-Cretaceous the processes had been undoubtedly going on for a long time previous to the formation of this conglomerate, even though they had not destroyed the integrity of the rocks nor succeeded in wholly separating the iron by concentration from the silica, and that a large part of the iron was wholly concentrated in pre-Cretaceous time, we may admit that the results of the pre-Cretaceous periods are rather more important in the introduction of iron into this conglomerate than the time since. But we also conclude that the processes of change have been going on as steadily in the iron

bearing rocks since the Cretaceous as previously,—not only in the fragments in this conglomerate, but also, necessarily, in the rock which was still in place.

POST-GLACIAL CHANGES IN THE IRON ORE.

From the time of the formation of the iron-bearing member to the latter part of the Keweenawan we have nothing definite by which to measure the progress of the degradational changes in these rocks; but at this time, if our reasoning is correct, the decomposition and concentration had already progressed to a considerable degree. From the Keweenawan to the Cretaceous, again, there is a gap in which there are no available records; but at the Cretaceous we find that the processes were going on as steadily as ever. From the Cretaceous on, there is no record till we come to the glacial epoch. So slow have been these stages that our studies have indicated, that the change since the glacial period can have very little effect; and yet there is evidence to show that it has still gone on, and with as great an apparent activity as ever. Occasionally, where the drift contains many fragments of the iron-bearing rock, a post-glacial conglomerate in small lumps has been formed. A case of this was seen by the writer on the line of the Duluth, Missabe & Northern railroad, a few miles south of Mountain Iron. The conglomerate was as firm as most of the ferruginous conglomerates of the Cretaceous. The fragments were of partially ferrated portions of the iron-bearing rock and of hematite; they were mostly angular, and with the finer matter were firmly cemented by iron oxide. This conglomerate formed a crust upon a large granite boulder, and had it not been for this circumstance its appearance of solidity was so great that it would have been somewhat difficult to believe it of post-glacial origin.

PERIOD OF FORMATION OF THE ORE-DEPOSITS.

The process of concentration of ore has gone on with few interruptions, on the Western Mesabi, from the period immediately succeeding the formation of the iron-bearing member, down to the present time. Any particular deposit, however, may have been begun and finished at any points within this period, or may have been in process of formation during the whole of this time. The great ore-deposits, for example, have been assumed to have had their real beginning in the disturbances which probably took place in the later Keweenawan

time; and yet the iron that was here concentrated had probably been slowly separating from the rocks for a long period preceding. The formation of these same deposits, moreover, was probably completed long before the glacial period, and yet since that time the processes have gone on in the adjoining rocks, less effective, but as active.

EFFECT OF THE GLACIAL ABRASION UPON THE ORE-DEPOSITS.

It is quite certain that the amount of ore upon the Mesabi range was considerably lessened by the scraping action of the ice-sheet. The ore offered practically no resistance whatever to such a tremendous grinding agent, and would have all been carried away were it not for the protective action of the harder rocks. These harder rocks, whether they were, as was often the case, a ridge of hard granite or schist to the north, or merely a hard rim of the iron-bearing member itself, bore the weight of the ice, and so the bodies of ore escaped destruction. For example, in the Biwabik group, the ores rest directly against the ridge of the Keewatin schists to the north; and at Mountain Iron the rim of hard rock forms an elevation which bounds the ore-basin on three sides. But at both these places there is evidence, of the same nature as is found elsewhere, that the glacier has really scraped off the topmost layers of the ore. At the Biwabik mine, there are included in the drift, which overlies the ore, large masses of paint-rock, yellow ore,

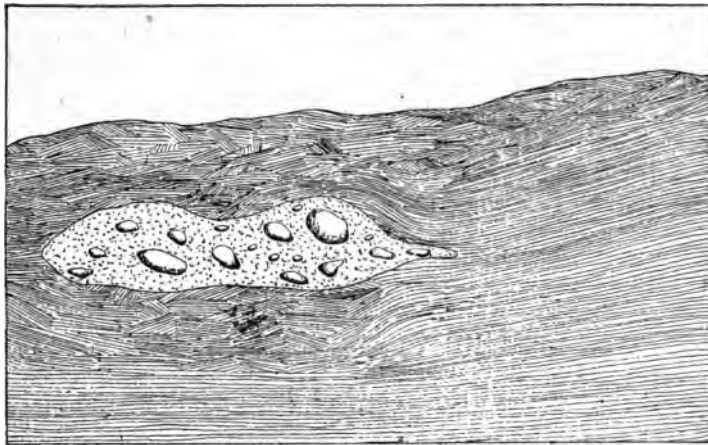


Figure 18.

East and west section of till in ore at Mountain Iron mine. To the north this tongue comes to the surface, so that this is a transverse section of it. Scale, 5 feet to 1 inch.

and even blue ore, in irregular bunches or in thin and broken layers. At the Mountain Iron mine the ore is mingled with the drift in the most intimate way at the surface. The surface covering of drift is full of large masses of ore; and into the ore below have been inserted wedges of the drift. In this case the wedge is usually transverse to the horizontal stratification of the ore, and by its insertion the stratification is bent and broken somewhat; but sometimes the wedge has been inserted between two layers and parallel with them, without disturbing the bedding in any great degree. (Figure 18). In still other cases sections in mining show wedges of till which run down vertically, transversely to the bedding, without disturbing it, as in Figure 19. Where these wedges have broken

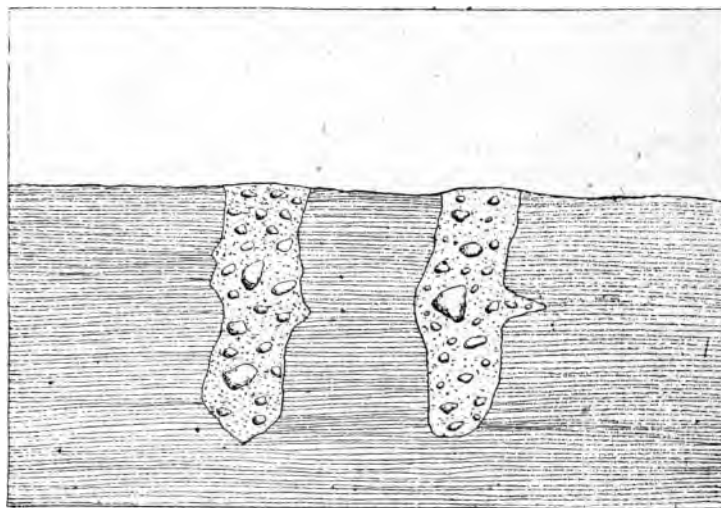


Figure 19.

North and south section at Mountain Iron mine, showing wedges of till in undisturbed strata of ore. Scale, 5 feet to 1 inch.

the stratification, it is probable that they were forcibly thrust into the ore; but when the bedding is not disturbed, there seem to have been produced, by the motion of the ice, empty fissures, which were afterwards filled with till. When the wedges are vertical, it is probable that the weight of the ice has produced the transverse fissures; when they are horizontal, the ice seems to have lifted up the topmost layers from those beneath, leaving an empty space between; and this empty space was subsequently filled with till, the cavity being considerably enlarged in the process of filling.

The formation of these narrow fissures conformable with the bedding is further shown by the occurrence of conformable sand-veins. They are found in considerable abundance near the surface (ordinarily within twenty feet), at the Mountain Iron mine. Many of them are quite conformable with the layers, and are persistent for considerable distances. The sand is white, with a slight yellowish tinge, and is usually very fine, the individual rounded grains being so small that their shapes can be well seen only by the aid of a magnifying glass. Many of these veins are from one to one and a half inches wide, and can be traced from twenty to fifty feet. Their true nature is shown by the transverse veins of the same material, with which they are associated, and sometimes connected. These transverse veins connect at the upper end with the surface of the ore and the bottom of the drift, and at the other with a conformable vein or an irregular pocket of sand. These pockets are also a very common feature

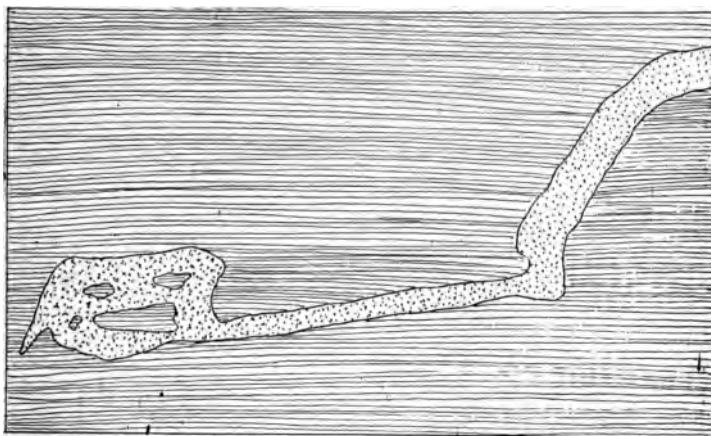


Figure 20.

Sand-vein in ore at Mountain Iron mine. Scale about 5 feet to 1 inch.

In these cases the fissures were too small to be filled by the direct packing of the glacier, but the glacial waters bearing in suspension very fine sand from the drift, have penetrated them. (See Figure 20). In considering the formation of these transverse and conformable fissures, without any disturbance of the bedding, it must be remembered that at the time of this action the ore was cemented with frozen water, and thus rendered rigid.

That the vertical wedges which are filled with till occupy transverse fissures which were caused by the increased weight of ice at the southern end of the Mountain Iron mine is further shown by the structure of the ore, as seen in a north and south section which was exposed, after some stripping and mining. The section is shown in Figure 21. From the base of the

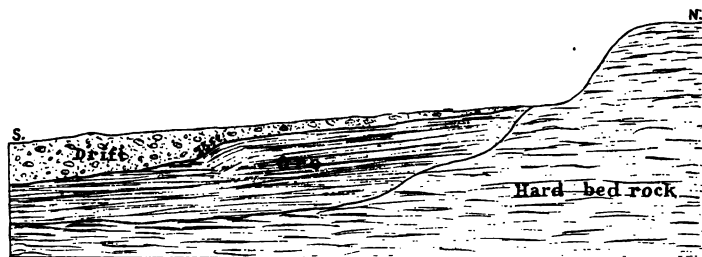


Figure 21.

Section at Mountain Iron, to illustrate the results of the glacial abrasion.

hard rock bluff which limits the ore-body on the north, the ore runs south, with a gentle slope, which is somewhat greater than the southward slope of the upper surface of the till, which here forms a scant covering. This is uniform for about four hundred yards. Then the till suddenly cuts down into the ore at a steep angle, making a drop of twenty or thirty feet; so that at the time that this observation was made the ore disappeared beneath the floor of the cut, and did not reappear. The surface, however, does not participate in this sudden drop, but maintains its uniform descent; and the thickness of the till covering consequently becomes increased by the whole amount of the drop. Where the drift has thus cut down across the nearly horizontally bedded ore, the violent nature of the process is evident. The layers, which run quite straight till they approach very near to the drop, are here bent down and broken, and in the drift are numerous masses of the ore, which have been broken off and mingled with it at the time of the shearing-down process. (See Fig. 22.) These phenomena show the following to have been the effect of the glacial abrasion here. The weight of the ice-sheet was chiefly borne, at the northern end of the deposit, by the rim of hard rock, especially the rock bluff. Nevertheless, the ice scraped off the more superficial parts of the easily eroded ore-body, and these fragments are still found in the drift. The surface that was thus removed left the space occupied by the ore lower than the surrounding rock, and at the cessation of glacial action it had the appear-

ance of a basin, surrounded on all sides by the rim of harder rock which was left as ridges; and this appearance it retains at the present time. But after this topmost portion was removed the pressure was rather forward than downward, in the immediate vicinity where the weight was borne by the hard rock-rim. The result was the lifting up of certain layers bodily for some little distance, leaving the permanent and conformable fissures, which were afterwards filled by the sand; or, almost immediately, by a lateral wedge of till. But at a certain

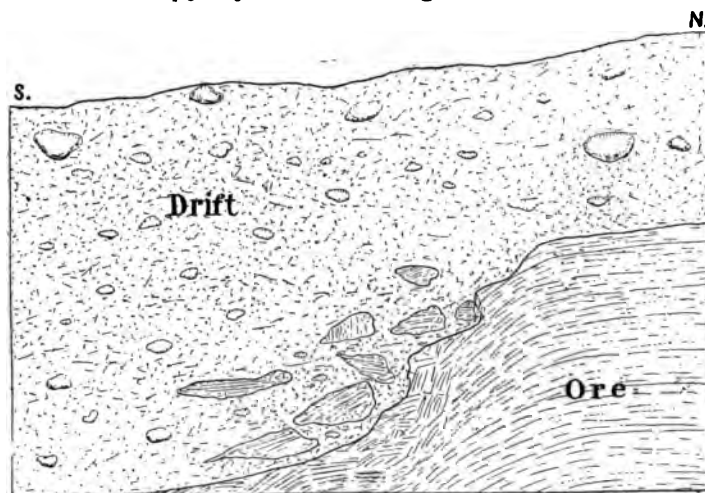


Figure 22.

Diagram, showing on a larger scale the drop (25 feet) which is seen in the profile of the ore in figure 21. This illustrates the manner in which the drift cuts down into the ore.

distance to the south the rock-rim became no longer able to support the whole weight of the ice, which thus came to rest partly upon the ore, and immediately, by the force of its weight, sunk twenty or thirty feet downward, and so continued. The effect of this increase of weight on the forward part of the ore-body produced, in that part of the rigid but brittle frozen mass further north, where the culmination of this strain came, transverse vertical wedge-shaped fissures, into which the till found entrance without serious rupture. Thus the undisturbed condition of the bedding next these till wedges is explained.

An ore-body which existed before the glacial action, but was without sufficient protection, might have been entirely removed and disseminated in the drift. It is probable that in every case where the granular blue hematite and other little-hydrated forms are encountered directly below the drift, there

has been removed a considerable portion of paint-rock and hydrated ore, together with an unknown amount of the blue ore itself.

Relation of the Present Topography to the Ore-Bodies.

It will be seen from the discussion of the condition of formation of the ore-bodies that the present topography, which is a very recent thing, being partly glacial and probably almost entirely accomplished since early pre-glacial time, can have little causal connection with ore-bodies which began to form in Keweenawan time. At the same time, the previously existing ore-bodies have undoubtedly influenced the topography, during its formation, and thus have some causal connection with it. Pre-glacial rain and stream erosion have had a greater effect upon the soft ore-bodies than upon the surrounding rocks, and so have excavated them to a greater extent, unless, as was probably very often the case, they were protected by a substantial capping of harder rock. Yet this erosion was not so great as the glacial erosion, for the great thickness of decomposed rock all over the country, deep under which lay both the hard rocks and the soft ore-bodies, formed a protective covering. But the ice-sheet, when it swept this covering away, had a discriminating effect upon the rocks below, in the way that has already been indicated. When a body of the soft ore was left with no protection from harder rocks, it was entirely swept away. Where the ore-body was surrounded on several sides by the protective covering, as at the Mountain Iron mine, there resulted, from the greater erosion of the softer parts, a rock-rimmed basin, in which the ore is found. When the protection consisted chiefly of a hard ridge on the north, as is the case at the Biwabik group of mines, perhaps aided by the harder rocks some distance south, but with no very important lateral support, the ice cut at its lower surface a plane slope. At the summit of this slope the weight of the ice was all borne by the hard ridge, but as the distance from it increased the weight must have been partly borne by the harder rocks to the south; or what existed intermingled with the ore-body on either side; or by the ore-body itself. In the shelter of these ridges of Keewatin schist are found many of the larger ore-deposits. So it happens that a gradual slope, preferably southern, especially if it has on either side slight elevations to give it a somewhat basin-like appearance, is considered on the Mesabi an important topographical aid in the discovery of the location of the ore-bodies.

ARTICLES OF COMMERCIAL IMPORTANCE, OTHER THAN IRON,
IN THE IRON-BEARING ROCKS.*Manganese.*

Manganese in small amount is disseminated through certain areas of the iron-bearing member. It is closely associated with the iron ore, in many places, especially in the ore-deposits of the Virginia basin. Here is the only place where it has been found in any appreciable amount. Through most of the mines in this basin the manganese ore occurs in the form of the small shining crystals of the peroxide pyrolusite, which are intimately mingled with the granular hematite, and in certain limited areas increase so as to form a large percentage of the mass. Such highly manganiferous masses have been seen by the writer at several of the mines in the immediate vicinity of Virginia, especially at the Rouchleau. On the Moose property, in the southeast of the southeast of section 8, T. 58-17, a pocket of nearly pure ore was found, in the midst of the larger deposit of iron ore. In prospecting this deposit in the summer of 1893, over a hundred tons of ore were taken out; of which analyses, the results of which were kindly supplied me by Mr. Horace V. Winchell, showed 53 or 54 per cent. of metallic manganese, together with a small amount of iron, and some phosphorus, the latter averaging about .07 per cent. Although this is the only place on the Range where manganese in merchantable quantity has been found, it often occurs incrusting the rock along joint-planes, in dendritic forms of an earthy variety of the oxide.

The method of formation of the manganese deposit at Virginia has already been hinted at, in discussing the fault at this place. The fact that it is situated in the midst of one of the largest iron ore deposits upon the Range, and that this is, so far, the unique location, points to the fact that the origin of the manganese has been dependent upon the same causes as that of the iron. The weakness of the fault line has induced the accumulation of the manganiferous solutions, which were at the same time highly ferruginous, and the oxidation along the fault zone has precipitated the manganese oxide, in the same way as the iron oxide. The constant association of manganese and iron in all horizons is well known, and the causes of their association and their separation have been well summed up by R. A. F. Penrose.* Manganese has a close relation and a chemical

* Report on Manganese, pp. 560-573. Vol. I, Ark. Geol. Surv. Rep. for 1890.

resemblance to iron. Both are taken into solution by the same solvents and are precipitated by the same causes. The waters which brought the iron solutions to the Virginia region also contained a small amount of manganese, in the same form; and when both arrived at the oxidized zone, by the release of the carbon dioxide which held them in solution they were precipitated together; the iron as the hydrous sesquioxide, the manganese as hydrated peroxide, or perhaps carbonate or sesquioxide. When the subsequent process of crystallization produced from the original earthy hydrated ore the granular blue hematite, the manganese also became dehydrated, and crystallized as the pyrolusite. Thus was formed the iron ore which is thickly sprinkled with the crystals of the manganese ore; and this is the most common form. In the pocket at the Moose mine, the ore has been obtained in the same way as that which is thinly disseminated; but there has been some modifying circumstance which has induced the precipitation of the manganese for a while separately from the iron. The cause of this separation probably lies in the slight difference of oxidability of iron and manganese. While the iron and the manganese are held in solution and are precipitated by the same agents, yet there has been noted a difference in their ease of precipitation. The oxide of iron is rather more easily precipitated than the oxide of manganese; and the carbonate of manganese appears to be a more stable salt under atmospheric influence than the corresponding iron carbonate. So it happens, as observed by Fresenius,* that freely moving waters, on coming into a region of ready oxidation, deposit first the oxide of iron, and, further on the carbonate or oxide of manganese. By the continuation of this process, separate deposits of iron and of manganese, on the same horizon and running into one another, may be formed. If, on the other hand, the metalliferous waters move very slowly through the oxidized region, the precipitation of the manganese and the iron in each supply of the solutions will be very near together, and the result of many such solutions will be the intimate mixture of the manganese and the iron. This must account for the difference in habit of the sparsely disseminated manganese and that of the ore-pocket. In the greater part of the weak zone which accompanies the fault line, the passage of percolating water is necessarily so slow that the manganese and the iron are precipitated very closely together; while the exceptional occurrence of the pocket demand the ex-

* Quoted by Penrose, *op. cit.*, p. 570.

ceptional conditions of freely moving water. The depth of the pocket shows that the channel of the waters must have been a fissure, since on both sides are the deposits of iron ore; and from the locality, almost exactly in the centre of the zone through which the fault passes, it may be suspected that this fissure was on the actual fault-plane.

The dendritic manganese which often lines the joints in the iron-bearing rock, and which is composed of wad or some other of the oxides,* has evidently been brought in the same way by waters which have found in these crevices a passageway.

Source of the Manganese.

From the intimate association with the iron of the manganese at Virginia, and from the evident fact that they were both deposited by the same percolating waters which had taken them into solution; moreover, from the incrusting of manganese in the joint-planes over a large part of the rocks, it is at first natural to believe that both the iron and the manganese were derived from the same source. The iron has been determined to have been in the iron-bearing member from the very beginning, where it originally existed in the form of a silicate, and from this form it has been altered and concentrated into its present form. If the manganese has had the same origin as the iron, we should expect to find it in the same conditions: first, almost invariably, in association with the original silicate of iron; second, in various forms of the rock which result from the metasomatic changes of this first rock; finally, in the completely decomposed and concentrated rock, we should expect to find it almost invariably associated with the iron ore. But the analyses made of the various primary and secondary phases of the iron-bearing rock have not reported any trace of manganese; the only traces found are in rocks which have been profoundly decayed or in other ways exposed to the free action of percolating waters. The amount of manganese in connection with the ore-bodies is variable, for while at Virginia it is common, at other places it is rare, and many deposits contain only the merest trace. So there is no evidence that the original source of the manganese was the same as that of the iron, *i. e.*, in the original condition of the iron-bearing rock. It must be remembered, however, that manganese is much rarer than iron, and that possibly quantities so small as to be overlooked are constantly associated with the less-altered phases

*Op. cit., p. 83.

of the rock, and that these small quantities, by the process of concentration, might become large enough to be recognized; but until this is shown to be the case the evidence points the other way,—that the original source of the manganese was not necessarily in the iron-bearing member. In this case, it must be that the waters, which bore the manganese in solution, and which undoubtedly were slowly filtered through the iron-bearing rocks, had previously dissolved the manganese in very small quantity from other strata. The very circumstance of the small quantity of manganese, in comparison with the enormous amount of iron, makes it easy to account for the former on this ground. The source from which such manganeseiferous solutions must probably have come is the overlying detrital slaty series, the underlying schists of the Keewatin, and the intrusive granite. It is extremely probable that the material of the slates consists almost entirely of the material from the schists and the granite, laid down in a finely comminuted state, without great admixture from other sources, except in the calcareous portions. So, to go a step further back, we must look to these older crystalline rocks for the source of the manganese in the very beginning. In the crystalline rocks manganese is very common, in the form of manganiferous silicates. A list of these silicates is quoted from Penrose.*

“Among the most common of these are: rhodonite; the manganiferous forms of pyroxene, amphibole and garnet; the manganiferous minerals of the olivine group, such as tephroite, roepperite, knebelite, danalite and helvite; the manganiferous epidote known as piedmontite; the minerals ilvaite, ardenite, trimerite, and numerous others.”

Besides the silicates, manganese often occurs in the form of carbonate, and occasionally as the oxide. Many of these minerals are found in the crystalline rocks of the Western Mesabi, especially in the variable and complex schists of the Keewatin. When the schists were eroded and laid down as slates, in a deposit of great thickness, the finer division of these silicates made the manganese more liable to decomposition and solution by percolating waters. When we consider the enormous lapse of time which has been required for the formation of the iron deposits, and that the same period must be allowed for the accumulation of the manganese, it is clear that the solutions derived from the manganiferous silicates of the slates have been quite sufficient to produce, under favorable conditions, the

*Op. cit., p. 545.

amount of manganese which we find; and that the agency has been simply that which has operated in the concentration of the iron—the percolating drainage waters.

We thus obtain an explanation of the occurrences. At Virginia, the great fault which traverses the present ore-bodies passed at its origination through an unknown but undoubtedly immense thickness of slates. These covered the iron-bearing member, not only to the west, where the slates exist at present, but to the east, forming a covering to the uplifted area. The fault weakened the slates, although probably in less degree than the iron-bearing member; as in the iron-bearing member, there was an increased circulation of surface waters, an increased solution of the former constituents, and an increased deposition of the concentrated products. As the covering of slates upon the Virginia area were slowly eroded, each horizon in turn was bared to the surface and profoundly decomposed; and during all this time the waters which had taken into solution the soluble parts of these decomposed silicates found one of their readiest passages through the fault-fissure. The materials deposited here would be chiefly iron, with some manganese; of these the iron was confounded with the vastly greater amount derived from the iron-bearing member itself; while the manganese remains conspicuous.

SILICA POWDERS.

When the iron-bearing rock has reached in a certain part, by perfect concentration, the condition of a chert, and subsequently disintegrates, there is formed a powder which consists essentially of silica, with a variable amount of impurities. The disintegration appears often to result in part from the dissolution of the carbonates which are very often associated with the cherty silica. These are generally in small bunches of crystals, minutely disseminated; so that their removal destroys the strength of the rock, which then easily crumbles away. The carbonate is generally siderite, and in the process of its dissolution, a small part is precipitated throughout the rock as oxide, between the grains of the silica; this minute amount of the oxide acts as a wedge, which forces the grains apart and thus the comminution become progressively finer. The size of the grains of the silica in the chert is such that when completely separated, the result is a powder of great fineness. An example of this is in the powder described on page 126, speci-

men 230, from near the Mesabi Chief mine, in section 23, T. 57-22. The following is an analysis of this by Mr. Alonzo D. Meeds:

ANALYSIS OF SPECIMEN 230 (CHEMICAL SERIES NO. 242.)

Silica.....	SiO ₂	98.17 per cent.
Sesquioxide of iron.....	Fe ₂ O ₃	1.03 " "
Alumina....	Al ₂ O ₃	0.50 " "
Lime.....	CaO	tr.
Magnesia...	MgO	tr.
Soda.....	Na ₂ O	0.25 per cent.
Potash.....	K ₂ O	tr.
Loss on ignition.....		0.19 per cent.
Total.....		100.14

This material has a possible economic importance, on account of the abrasive qualities of the powder, should it be found, on further exploration, in sufficient quantity and of as great purity as the sample analyzed. This class of abrading and burnishing powders is already largely used. The most widely known is the tripoli powder, chiefly quarried near Seneca, Missouri, and found in many other places in the same region. This powder is the result of the alteration of a chert, "white, gray, or yellow, occasionally rose or flesh-colored," which is among the most important ore-bearing rocks in south-western Missouri.* In the nature of its immediate origin, it is thus identical with the Mesabi powder; it also resembles it very closely, being of the same cream color. The almost exact identity of chemical composition is shown by the following analysis of tripoli, taken from the pamphlet of the American Tripoli Company, at Carthage, Missouri.

ANALYSIS OF TRIPOLI.

Silica.....	SiO ₂	98.100 per cent.
Oxide of iron {	Fe ₂ O ₃	0.270 " "
	FeO	
Alumina.....	Al ₂ O ₃	0.240 " "
Lime.....	CaO	0.184 " "
Soda.....	Na ₂ O	0.230 " "
Water and loss on ignition.....		1.160 " "
Organic matter		0.008 " "
Total		100.192

Silica soluble in 10 per cent. solution of caustic soda boiled for three hours.

*Geol. Survey of Missouri. Vol. 1, p. 403.

Another analysis from the same place (at Seneca) is as follows:*

Silica.....	SiO ₂	98.28	per cent.
Alumina.....	Al ₂ O ₃	0.17	" "
Sesquioxide of iron.....	Fe ₂ O ₃	0.53	" "
Lime.....	CaO		Very slight trace.
Magnesia.....	MgO		Extremely slight trace.
Potash.....	K ₂ O	0.17	per cent.
Soda.....	Na ₂ O	0.27	" "
Loss on ignition.....	(H ₂ O)	0.50	" "
Total.....		99.92	" "
Water at 110-115° C.....		0.21	" "

In Arkansas, similar deposits are found at various places, and, as in Missouri, they are the result of the decomposition of a chert. A sample of pure white powder from one of these localities gave the following results:†

ANALYSIS OF SILICA POWDER FROM ARKANSAS.

Silica.....	SiO ₂	97.32	per cent.
Alumina.....	Al ₂ O ₃	1.61	" "
Sesquioxide of iron.....	Fe ₂ O ₃	0.35	" "
Lime.....	CaO		trace
Magnesia.....	MgO		slight trace
Potash.....	K ₂ O	0.13	per cent.
Soda.....	Na ₂ O	0.12	" "
Loss on Ignition.....	(H ₂ O)	.63	" "
Total.....		100.16	per cent.
Water at 110-115° C.....		0.029	" "

Up to the present time, however, the Arkansas deposits have not been extensively worked, partly, perhaps, on account of the lack of transportation facilities.

* Griswold on Novaculites. Ann. Rep. Ark. Geol. Survey for 1890, Vol. III, p. 367.

† Griswold, op. cit., p. 368.

CHAPTER XI.

ORIGIN OF THE IRON-BEARING ROCK.

The origin of the iron-bearing rock has long been a subject of doubt, discussion, and speculation, for the original characters are not plainly seen, even in a comparatively careful examination. It will be the object of this chapter to attempt to furnish some evidence as to the probable original nature of the rock and the origin of the iron.

One of the most striking things about the iron-bearing member is its individuality. While it has not been clearly made out heretofore to what this was primarily due, yet it has always been possible to recognize it as totally distinct from the associated rocks. The contact between it and the quartzyte below and the slates above appears to be generally well marked, and neither of these members have any resemblance to the greater part of the iron-bearing member. This same characteristic has been noted by Irving and Van Hise for the corresponding rocks of the Penokee series.*

The present material of the iron-bearing member has been found to be the result, almost entirely, of internal metasomatic changes, which have so altered the rock that few traces of its original structure remain. These changes have been effected by the ordinary agents of atmospheric decay, and these have acted upon the other rocks of the series as well as upon the iron-bearing member, but without producing in this latter case any very great effects, or at all obscuring the original structure, in the larger part of the rocks. The original iron-bearing rock, then, must have been of peculiarly unstable nature, strikingly different from the commoner detrital rocks with which it is associated. It was not originally a quartzyte, as has sometimes been supposed, for the main body of the quartzyte is

*Tenth Ann. Rep. U. S. Geol. Survey, p. 380.

quite fresh and unaltered, showing distinctly every original detrital grain. Near the contact of the quartzite with ore-bodies, there has sometimes been a slight replacement of the silica by iron, and, indeed, specimens might be found which would show every stage of the change from the quartzite to iron ore;* but this change is local and superficial, and is never found within the quartzite itself. The sharp distinction between the original nature of the quartzite and that of the iron-bearing member is well shown by those specimens from the iron-bearing member, near the contact with the quartzite, which contain scattering grains of detrital quartz, such as make up the quartzite. These grains are usually fresh and little altered, and are sharply contrasted in the sections with the rest of the material, which is all of undoubtedly secondary origin. This secondary material is mainly silica, which is usually finely cryptocrystalline, and in this there is finely disseminated or bunched iron oxide. The change which has altered the original characteristic materials of the iron-bearing member to these secondary products has not affected the truly detrital quartz, which has been present in association with the other materials from the very beginning.

For the same reasons, the rock could not have been originally a simple argillaceous sediment, for the presence of the slates in great thickness above, practically unaltered and distinguished by the most evident of characters from the typical iron-bearing rock, shows that the two could not have been primarily of the same nature. The calcareous layer at the very bottom of the slates is suggestive, and is undoubtedly important for the purposes of our inquiry; but there are insurmountable objections to considering the iron-bearing rock as having been of a simple calcareous nature. One is the distinction which exists between this horizon of impure limestone and the typical rock of the iron-bearing member beneath, both in structure and chemical composition. The limestone retains most of its original structural peculiarities, so that its nature is readily recognized; but the iron-bearing member, near the contact, has the same peculiarities as in the central parts of the horizon. It is marked by the ground mass of finely divided silica, through which are scattered the granules, made up of silica, the various forms of iron, the green chloritic substance, with the secondary products. The analysis shows a difference

*Twentieth Ann. Rep. Geol. and Nat. Hist. Survey of Minnesota, p. 140.

as great. In the iron-bearing member there has never been found by analysis more than a slight trace of lime, although microscopic sections have been made which show a considerable quantity of this carbonate. In these cases, however, the distribution of the calcite shows that it is an impregnation, derived from another source—probably the calcareous layer of the upper slates itself—and that it is not indigenous in the rock. The small amount of calcite which is found in analyses is seen under the microscope to be of a secondary nature, resulting from the disintegration of the original green chloritic substance. It cannot be affirmed that the original rock was not calcareous, but it is certain that the essential characteristic, which has brought on the metasomatic change, was not its calcareous nature. It is true that the formation of ore-deposits through the replacement of calcite by iron is very common, as has been abundantly proven in many cases;* but on the Mesabi range the features of ferration are totally different from those which are found in these replaced limestones. Had any such replacement on an extensive scale taken place, we should expect to find the layer which is now an impure limestone also replaced, since it overlies the main body. To this objection it might be well replied that the close grained overlying slates have acted as a protection against the complete changes, and that the ferrating waters need not necessarily have come through the slates, but have entered at the outcrop of the permeable strata, and from there have penetrated to the more remote parts. And, indeed, the fact that in parts this layer has been ferrated to a considerable extent, and the lime replaced by iron carbonate, shows that there has actually been some such process, and suggests that the patches of little-altered limestone are accidental residual fragments. But in the main body of the iron-bearing member a still greater obstacle to this view is found. In ore-bodies, which owe their origin to the ferration of limestones, the iron is derived from extraneous sources, and penetrates into the limestone strata by reason of their permeability. In the Mesabi iron-bearing rocks, however, the iron is found to have existed in the rocks from the beginning, so far as can be seen, although in a disseminated condition; and the ore-bodies have formed by concentration of this scattered iron. In the concentration, moreover, there has been a replacement of certain parts of the rock by iron; but in

*Kentucky Geol. Survey. Report of Progress, Vol. III, New Series; by N. S. Shaler; 1877, p. 164.

this case it is silica that has been replaced, and this silica itself is a secondary product. We can find no analogue of this process in the proven cases of the formation of ore-deposits by the replacement of limestone.

The theory of the formation of the ore-deposits by the replacement of a limestone was that first adopted by Prof. R. D. Irving,* but he afterwards abandoned it, considering that the original rock must have been an iron carbonate and not carbonate of lime. Prof. N. H. Winchell† also suggested a theory similar to this as the possible origin of some of the Minnesota ores. This theory, however, did not ascribe all of the phenomena to the process of replacement, but considered that the banding was original in the rock, and that the difference between the bands was due to the original distribution of impurities in varying quantities in the alternating layers.

Since we cannot, then, ascribe the origin of this rock, in the light of our present knowledge, to any of the ordinary forms of the commoner sedimentary rocks, we are driven, if we still hold the rock to be sedimentary, to the more unusual forms of sediments, namely, those of chemical or organic origin.‡

The various theories of chemical origin have been more earnestly urged and have met with a more general favor than any other. Careful observation has in nearly every case led to this belief; for both the field characters and the microscopic peculiarities of these rocks are such as are not compatible with any theory of direct sedimentation, but point to an immediate chemical source. One of the most evident of these characters is the ordinary finely cryptocrystalline or chalcedonic condition of the silica, which cannot represent directly clastic material.

The principal theories of chemical origin of the iron-bearing rocks, including the ores themselves, may be separated into two chief divisions. First, those which assume the ores and the iron-bearing rock to have been precipitated in practically their present condition, and to have undergone little change since that time. This view has been chiefly championed by N. H. and H. V. Winchell, and was originally applied to the ores of the Vermilion in Minnesota,§ but was afterwards ex-

*Origin of the Ferruginous Schists and Iron Ores of the Lake Superior Region. *Am. Jour. Sci. (III)*, Vol. XXXII, Oct., 1886.

†Fifteenth Ann. Rep. Geol. and Nat. Hist. Survey of Minnesota, p. 246.

‡Tenth Ann. Rep. U. S. Geol. Survey, p. 380.

§On a Possible Chemical Origin of the Iron Ores of the Keewatin in Minnesota. *American Geologist*, Vol. 4, pp. 291-300, November, 1889. Also in Bulletin No. 6 of the Minn. Geol. Surv., 1891, pp. 391-399.

tended to the Mesabi ores.* Briefly stated, this theory explained the origin of the banded silica and iron by direct precipitation from the waters of a hot primordial ocean, highly saturated with the minerals of the crust with which they came in contact. Alternating conditions produced from these waters alternating precipitations of iron and of silica. These alternations continued throughout the whole time of the formation of the iron-bearing rock, and the banding thus represents the original stratification. Inasmuch as the present discussion is confined to the Mesabi ores, the possibility of such an origin for the Vermilion ores will not be fully discussed. The writer, however, following the expressed opinion of nearly all the Lake Superior geologists,† and for many private reasons, which do not need to be detailed in this paper, believes that the iron-bearing rocks of the Mesabi and of the Vermilion have originated in the same manner, and that whatever restricts the theories of origin on the Mesabi, must be applied to the Vermilion also.

The principal reasons for holding this view of direct precipitation have been:

1. The regularly alternating bands of the "jaspilite" of the Vermilion, which has been taken *a priori* to be original stratification, and hence must be explained by the alternating deposition of iron and silica from the waters of the ocean. Since this iron and silica was found to be in a condition which was almost surely the result of direct chemical precipitation, and could in no way be assigned to the sedimentation of detrital material, it naturally followed that the oceanic waters had been the agents of this precipitation. But for this purpose it was

*Iron Ores of Minnesota, Bull. No. 6, Geol. Surv. of Minn., p. 144.

† N. H. and H. V. Winchell, p. 144, v. s. "We see no reason to exempt the Taconic ores from those methods and principles that we have found obtained in Keewatin time. We see, on the other hand, only evidence to convince us that the Taconic ores date from the origin of the rocks themselves, and that the conditions that governed the origin of the rocks were but a modification of those that governed the accumulation of the Keewatin rocks."

C. R. Van Hise, Iron Ores of the Marquette District of Michigan, Am. Jour. Sci., Vol. XLIII, February, 1892, p. 130.

"The ores of the Vermilion Lake district have been studied by us only in a general way, but so far as our investigation has gone all the facts bear toward the conclusion that the principles here hold which are applicable to the other iron-bearing districts of the Lake Superior region."

then necessary to imagine that the condition of oceanic waters was entirely different at the time of the formation of the ores from the condition at present,—that they were still intensely heated, and highly charged with acids, and the minerals which these materials held in solution.*

2. A section of the siliceous part of a typical Vermilion “jaspilite” contained the silica in a form which was held to indicate that the silica was precipitated in the amorphous form, in the shape of spherical minute globules, to the compression of which the occasional hexagonal outlines of the present grains was thought to be due.† In the section examined the silica was held to be amorphous, and not crystalline, (1) by the highly colored concentric rings which each grain showed in in polarized light, and (2) by the absence of fluid or gaseous inclusions.

To the first reason the answer is of course that the *a priori* assumption that the bands were original sedimentary layers is not warranted. Upon the Mesabi the whole process of the growth of these bands by the process of concentration along parallel lines of weakness has been carefully observed; the final result of this concentration has been to produce in certain phases alternations quite as fine as those of the Vermilion rock, and it is highly probable that both were formed in the same way. In the original condition of the rock upon the Mesabi, these bands do not exist, and they are well developed only in the more advanced stages of change. Upon the Vermilion the changes have gone on more completely, and under slightly different conditions.

Upon the Mesabi, again, the condition of the strata associated with the iron-bearing member are such as to forbid the assumption of the heated and turbulent primordial ocean, which is necessary for the direct precipitation of both iron and silica. Before the deposition of the iron-bearing rocks, the sediments were of sand,—just such sand as is deposited at the present day. The sharply outlined rounded form of the original grains shows that there was no appreciable corrosion by oceanic waters before deposition; while if the waters had been in the condition supposed by the theory under discussion, these grains must have been entirely dissolved. If the silica of the iron-bearing rocks‡ is still considered to represent a sudden change

* Iron Ores of Minnesota, p. 75.

† Iron Ores of Minnesota, p. 74.

‡ H. V. Winchell. The Mesabi Iron Range. Twentieth Ann. Rep. Minn. Survey, p. 138.

from the conditions of deposition of the originals and grains of the quartzite; and that under these changed conditions the waters were capable of dissolving silica and precipitating it in the finely divided cryptocrystalline or chalcedonic form in which it is usually found, there is another obstacle in those parts of the iron-bearing rock, near the contact with the quartzite, which contain in the ground-mass of finely divided silica scattered grains of detrital crystalline material, exactly like those found in the quartzite beneath; with their outlines regular and uncorroded, and exhibiting no sign of any transition to the finer variety. It thus seems clear, if the iron-bearing rock is considered truly sedimentary, that the conditions of temperature and solvent power of the water were nearly the same during its formation as during the deposition of the basal quartzite; and these conditions were not evidently greatly different from those of the present day. The rocks above the iron-bearing member show the same conditions of ordinary sedimentation, and the existence of the impure limestone belt, immediately above, is especially opposed to any extraordinary conditions.

The condition of the silica, which was the second chief reason urged in favor of its chemical precipitation, has been subsequently shown to have been misunderstood. Exceptions to the observations of Dr. Hensoldt, who made the original investigation, have been taken by Professor C. R. Van Hise,* and subsequently and independently, by Dr. U. S. Grant of the Minnesota survey. Of the two reasons that were given for considering the silica as amorphous instead of crystalline, the first, the polarization phenomena, was found to be due to the thickness of the sections examined by Dr. Hensoldt. Thinner slides showed the ordinary polarization phenomena of quartz. In regard to the second reason, it was found that the quartz actually contained numerous liquid inclusions.

Nearly all of the silica of those phases of the iron-bearing rock which have gone far in the process of change is made up of these interlocking quartz grains. In less advanced stages the silica grains are much smaller in size and less highly crystalline, the crystallizing motive often having worked so little that it is hardly distinguishable from truly amorphous silica; but the larger grains which make up the "jasper" are never of this variety. Since these larger grains are, then, not original, but

*Ann. Rep. Arkansas Geol. Survey, 1890, vol. III., p. 184.

are formed during crystallization by the union of many smaller particles, neither their size nor their shape can be taken as any indication of the conditions of their original deposition.

The second class of theories of chemical precipitation asserts that since the precipitation of the iron and silica, there have been great metasomatic changes, which have brought the rocks to their present condition and have induced the formation of the ore-bodies. This is the view which has been adopted by Irving and Van Hise, in their monograph on the Penokee-Gogebic iron range, and extended to the Animikie series in Minnesota.* Their opinion of the origin of the chief constituents of the iron-bearing rock, the iron and the silica, may be best learned by quotations. Concerning the original form of the iron (which has subsequently concentrated into the present deposits), the following is a concise statement:†

“Whether the iron was originally precipitated as a carbonate, or was decomposed and precipitated as a hydrated sesquioxide, just as limonite now forms from iron carbonate in places where bog ore is depositing, is uncertain. If the latter is taken to be the case, and it is perhaps the more probable supposition—it is necessary to believe that the organic matter with which the limonite was associated reduced the latter to the protoxide, and by decomposition furnished the carbon dioxide to unite with the protoxide, and thus reproduce iron carbonate.”

Concerning the origin of the silica, the discussion is summed up as follows:‡

“Our conclusion is then: First, that the chert was mainly deposited simultaneously with the iron carbonate with which it so closely associated; and second, that it is probable that the chert is of organic origin, although we have no positive proof that it is not an original chemical sediment, while it may in part be from both sources.”

The conditions which are supposed to have prevailed in the time of the precipitation of these materials, while somewhat different from those of the present day, do not involve so great a departure from the uniformitarian belief as do the theories of direct precipitation in the present form. It is supposed that the atmosphere was more highly charged with carbon dioxide than at present, and that the general temperature of the earth's crust was somewhat higher. Under these conditions atmospheric waters, by virtue of the greater amount of carbonic acid, would decompose the rocks far more actively than at present,

*Tenth Ann. Rep. U. S. Geol. Survey. The Penokee Iron Bearing Series, by R. D. Irving and C. R. Van Hise.

†Ibid., p. 396.

‡Ibid., p. 397.

and these waters, escaping into the sea, would cause the ocean to become charged with the iron solutions. It is, however, added, that although these conditions were probably present, yet the deposition of the original iron may be accounted for by the same process as carried on under ordinary conditions at the present day, and which leads to the formation of bog ores. At any rate, it is supposed that the waters of the ocean were in a condition which permitted the existence of abundant organic life.*

From these homogeneous original rocks, which, so far as can be seen, were originally of iron-carbonate and silica, metasomatic changes have produced all the multitudinous phases of the iron-bearing rocks, including the ore-bodies.

Since so far we have discussed the various possibilities on general grounds only, reserving the specific study which points to the probable origin for the final discussion, we will here mention only the general objections to this explanation. These objections have already been pointed out by other investigators to the theory of a direct precipitation in oceanic waters. We have at the present time no instance of a precipitation of this exact kind. The precipitation of iron oxide from waters bearing iron carbonate in solution is one of the most common processes in nature, and has produced a not inconsiderable supply of ore, locally; but the conditions under which such ores are precipitated are not such as obtain in the oceanic waters, and it is difficult to understand how such a precipitation could come about. When chalybeate waters emerge from the rocks or the soil from which they have obtained their iron, they are soon exposed to the oxygenating influences of the atmosphere, their carbon dioxide escapes, and the iron which the waters held in solution by virtue of this is precipitated as the hydrated sesquioxide. If the water has thus found its way into a running brook, the surface of the pebbles of the brook for some distance become coated with the oxide. The motion of the water quickly precipitates, by bringing successively all parts of the water under the oxidizing influence, all the iron that is unstable under these conditions. If the waters ooze into a shallow swamp or bog, the oxidation is somewhat slower, but since the iron-bearing waters remain in the same position till the process is completed, the amount of iron eventually concentrated is much greater, and the continuation of the process brings about a workable deposit of ore. But nearly all the iron which is

*Ibid., p. 395.

thus brought by waters to the surface is very quickly precipitated in these ways, and very little of it can ever find its way into the sea. It may be even possible that stagnant lakes, or land-locked lagoons, might form upon their beds a precipitate in this way, but we cannot easily conceive of its taking place in the ocean. What iron reaches the main body of the ocean is quickly diluted by the great mass of water, so that the amount of iron in the ocean at the present time is very small, and would have to be increased enormously for any precipitation to take place; and this increase would seem to necessitate conditions entirely unlike the present, or even those which are supposed by the advocates of this explanation to have existed. It is difficult to understand how strata which are known to extend somewhat uniformly for a hundred miles, and are nearly a thousand feet thick, can have been wholly or in part formed by any such precipitation. The extent and uniformity of the strata, as well as their thickness, do not accord with the idea of land-locked lagoons; and yet this seems the only possible explanation. Above and below the iron-bearing member are strata in which there is neither iron nor cryptocrystalline, chalcedonic, or amorphous silica, and yet they were formed, according to this theory, in the same oceanic waters.

If it is supposed that the quartzite was first deposited in the open sea; that at the close of the deposition an elevation changed this region to coastal swamps, in which the rocks of the iron-bearing member accumulated; and that at the close of this period a subsidence brought on the formation of the simple detrital series again: this explanation may be held to explain the origin of the iron, but the silica can hardly be thus accounted for. J. W. Judd,* in discussing this question in connection with the theories of the origin of the Northamptonshire iron ores, shows that iron is thus found in chalybeate springs and in still bodies of water; but not in running streams or other moving water, because here the access of oxygen precipitates the iron as hydrated peroxide.

- * * * "I do not believe, therefore, that the waters of any great river, or of the sea, can ever contain more than the minutest trace of iron in solution." * * * * But the Northamptonshire iron ore contains "from 30 to 50 per cent. of the metal; a rock which we cannot possibly conceive of as being deposited in an open sea or river."

We thus find ourselves obliged to lay aside the theories of chemical precipitation of the iron in the form of oxide or car-

*The Geology of Rutland, etc., p. 130.

bonate. Besides the explanation which we shall present, there is only one other theory of the origin of the ores which has received firm support. This is the theory of their eruptive origin. That the iron-bearing rocks of the Lake Superior region were erupted in practically their present condition was early held by Professor J. D. Whitney,* and Foster and Whitney.† Afterwards the view was adopted by Dr. M. E. Wadsworth for the Marquette District.‡ Dr. Wadsworth believed that the alternating bands of silica and iron were the result of the flowage of the original molten rock (subsequently greatly modified by the chemical action of the percolating waters), and analogous to the flowage banding of rhyolites and trachytes, among acknowledged lavas.§ For this species of volcanic rock, having a higher content of silica than the rhyolites, he proposed the name of "jaspilite." ||

The objections to the directly eruptive origin of the Mesabi iron-bearing rock are numerous and rest in part upon the same grounds that show the directly chemical origin to be probably not the true explanation,—the circumstance that the banding is not primary, but secondary, and so can no more be regarded as the fluidal structure of a lava than as the layers of an original chemically precipitated rock.

Having thus briefly spoken of the most prominent theories which have been introduced to explain the origin of the ores, and named the objections to which, on general grounds, they are severally open, we will proceed to discuss the results to which our investigations have led us, and to offer an explanation, which does not come under any of the theories discussed or any of the objections named.

It became evident to the writer while engaged in field work that all of the multitudinous kinds of rock which were associated with the iron deposits passed into one another by gradual changes, and were probably derived from a single original type by the alteration of atmospheric influences. The recognition of this fact is considered to be the most important part of the present discussion, since it effectually does away with all at-

* Metallic Wealth of the United States, 1854, pp. 37, 429-437, 477, 478.

† Senate Documents, Spec. Sess. 32nd Congress, III, 1851.

‡ Bulletin of the Museum of Comparative Zoology at Cambridge, 1880, Vol. VII, (Geological series, Vol. I.) First paper, Proc. Boston Soc. Nat. Hist., 1880, XX, 470-479.

§ Further studies and evidence caused Wadsworth to abandon his former ideas and to hold that most, if not all, of these iron rocks were of mechanical origin, but that they had subsequently been modified greatly by chemical agencies. (See Report of the State Board of the Geological Survey, Michigan, 1893, pp. 104-121).

|| Bull. Mus. Comp. Zool., Vol. VII, p. 76.

tempts to explain the formation of the rocks in their present condition, which must necessarily lead to the greatest confusion. At the time of the discovery of the fact of the derivation of the rocks from a single original type, the writer's acquaintance with the literature of the region was incomplete; and it was not until some time after this that he had opportunity to read the monograph on the Penokee-Gogebic iron range, by Irving and Van Hise;* in which for the first time he found that the same proposition had already been conceived and established for the iron ranges of the South Shore, and had been extended to the Animikie series in Minnesota. That the fundamental principle in the monograph referred to and in the present paper should be the same and should have been arrived at independently in each case, is significant as to the correctness of the conclusions.

In the course of our comparative study of the rocks of the Mesabi, however, it has been possible to go somewhat further back in the history of the iron-bearing member than has been done for the Penokee-Gogebic region. The iron carbonate, which, according to the researches of Irving and Van Hise, was the oldest type which could be found, and therefore was held to represent nearly the condition of the original rock, has been found on the Mesabi to be in nearly all cases of undoubtedly secondary origin, and to have been formed by the carbonatization of iron oxides. It was found, moreover, that all of the constituents of the rocks, including the iron carbonate and oxides, and the silica, could be shown to have been derived from a substance which appeared to be original, and which in the description has been designated as "greenish chloritic substance," or "original green silicate."

This substance was thickly scattered in bunches through the less altered rock, but from the very beginning began to undergo rapid disintegration. The chief products of this decomposition were silica, in the cryptocrystalline to nearly amorphous form, and the oxide of iron; there were also various secondary products resulting directly from the change, or from the combination of the separated products. These were calcite and siderite in small quantities, actinolite, epidote, residual clayey matter, and the like. The details of these changes have already been gone into, as have been the various stages which mark the striving towards stability of the loosely arranged products of

*Tenth Ann. Rep. U. S. Geol. Survey.

the decomposition, so that they need not be repeated here; and it only remains to inquire more minutely into the nature of the green material, and to discover, if possible, its origin.

In the macroscopic and microscopic features of the great mass of the iron-bearing rock there is no evidence of its original nature. All the constituents are evidently of secondary origin, and suggest no more a detrital than an igneous rock. Irving and Van Hise have noted the same characteristic for the rocks of the Penokee-Gogebic iron-bearing member.* The result of the studies of the Mesabi rocks led at first to the assumption that the original rock, of which the structure was thus almost totally obliterated, and which was represented only by the "greenish chloritic substance," might be either an excessively basic lava, or some peculiar kind of sediment, outside of those which have been discussed. It was evident that the original rock had been one of excessive instability under atmospheric influences, and, therefore, was formed under somewhat extraordinary conditions. The idea of a lava therefore became to be seriously considered as the solution to the problem. It is generally acknowledged that portions of the inner crusts are more highly basic than any identified volcanic rocks; and it is regarded as highly probable† that the interior of the earth may be formed almost exclusively of the simple metals, especially iron. A lava, then, originating in the deeper regions, might be so composed that while it would be quite stable under the freedom from atmospheric influences in which it had its beginning it would be extraordinarily unstable under conditions of freer oxidation. It might be basic from an excess of iron, and this iron might be originally in the protoxide form, combined with silica to form proto-silicates. From this uncrystallized, undifferentiated mass, which the original "greenish chloritic substance" might represent, there would be formed by decomposition exactly the same materials which we have—the separation of the silica and the iron oxides, and the removal of the more soluble decomposition products. Neither the thickness of the iron-bearing member nor the extent of the formation could be urged as objections to this hypothesis, for even in historic lavas such quantities of erupted material may easily be paralleled, without appealing to the unusual conditions which may well have existed at this early period of the earth's history.

*Tenth Ann. Rep., *supr. cit.*, p. 380.

†De Launay: *Formation des Gites Métallifères*.—Paris, 1893. Posepny: *The Genesis of Ore-Deposits*, p.

The other possibility was that there might be formed, in the depth of the ocean, a class of sediments distinct from those which had yet been proposed; that detritus of certain compositions might, by uniting, undergo chemical changes under certain conditions, and produce a compound which might be stable in the ocean depths, but unstable when the region was elevated, and brought within the domain of freer oxidation. This compound, again, might be represented by the greenish chloritic substance, and the results of its decomposition, again, would be exactly those which we find.

It has been already stated that at the lower edge of the iron-bearing member there are intermingled with the non-fragmental material grains of truly detrital quartz, like that of the underlying quartzite. But since these grains did not evidently lie in any well-defined zones, they were regarded as equally applicable to either theory. On the eruptive hypothesis, a lava, at its lower contact, might take up into its mass some of the sand from the sand-beds over which it flowed. These grains would work up for a short distance from the contact, and in the viscous state in which this outer edge of the cooling mass would be, the heat would be insufficient to melt, or even greatly corrode them. On the sedimentary hypothesis, on the other hand, the scattered grains, diminishing as the distance from the basal quartzite increased, would be held to indicate the progress of the change of conditions from those necessary for the formation of a quartzite to those which governed the new sediment. This change was then probably in the form of a subsidence of the ocean floor, and the sand-grains indicate the last contributions of sediment from the shore-region, where the deposition of sand still went on.

But these possibilities were again limited by the discovery, near the *upper* contact of the iron-bearing member, of scattered material which was almost certainly of a detrital nature, surrounded as before, by non-fragmental secondary material. In many cases this was suspected, but in one the evidence seemed quite satisfactory. This was in the specimen called 53-1, which was from the iron-bearing rock at the immediate contact with upper slates, which are represented by 53-2. From 53-1 seven sections were made, of which one has already been described. (See page 68). The rock was less altered than any other specimen found in the whole iron-bearing member, probably on account of the protective capping of the slates to which it lay so closely. It seems clear from an examination of this that the

rock was of a detrital nature, for the forms which are scattered through the rock have rounded shapes and positions which are those of detrital grains. Naturally, these grains are not of quartz, like those at the lower contact, but suggest the approach of the conditions which produced, first, the bed of impure limestone, and then the argillaceous sediments into which this graded. The grains of detrital form are of two kinds.—First, those of a crystalline carbonate, which may be calcite, but from the analysis of 53-2 (see p. 70), is probably in part at least magnesite. In some of the sections these grains have been found to increase in numbers locally to such an extent that they formed a solid layer, very thin, but continuous, which in this case was exactly like the dolomitized limestone above, but was limited above and below by the characteristic secondary silica of the iron-bearing rock. There can be no doubt that this is detrital material, originally lime, which subsequently to its deposition has become dolomitized and crystallized.

The second class of detrital grains in these sections are those which are composed principally of the "greenish chloritic substance" which is found all through the least altered parts of the iron-bearing member, in whatever horizon. Some of these are somewhat shattered and torn, but many show rounded and uncorroded outlines which appear to be those of detrital grains. In many cases where the silicification of the original green material has been begun and even carried on to a large extent, there are still preserved the outlines of an original rounded body, which seems to have been made up almost wholly of the original green substance.

The discovery of such detrital material is not explicable by a consideration of the original rock as a lava, and hence we are driven to accept the other possibility,—that the rock was a sediment, formed under the conditions which have been hinted at.

With an especial view to the ascertaining the nature of this original mineral, as well as advice upon other points, selected sections, all of which have been described at some length, were sent to Dr. J. E. Wolff of Harvard University, who kindly examined them and returned the following comments:

"*Section 78.* Composed essentially of aggregate silica. The rounded grains have typical rolled clastic outlines; are filled with fine aggregate silica and dotted with black ore. Cement is pure chalcedonic silica, with occasional rhombs of carbonate and octahedra of magnetite, both of which, from their perfect crystal form, must have formed in place and contemporaneously

with the silica. Other carbonate areas, irregular, are within the grains; and the magnetite or iron ore dots within the same are residual.

"125. Cement much coarser grained silica than in 78—quartz, probably—sometimes arranged around fragments in brickwork structure, showing secondary deposition around these bodies. The round grains are here a brownish-green to clear green color, partly isotropic, partly aggregate polarizing, in feebly-polarizing dots and specks. Hardly any pleochroism; no cleavage. They resemble in all physical characters *glauconite* grains. In some cases a little carbonate is mixed with the probable *glauconite*.

"215. Rather indistinct clumps of limonite or hematite, with the same siliceous ground-mass. Outline of clumps too vague to identify directly with the round grains of 125, without transitional forms.

"213. Same as 215. The rounded outline of some clumps shows that they are those of 125. Carbonate seems secondary in these clumps.

"27-A. Here the round clastic bodies are distinct, some hematite, some magnetite. Silica very fine-grained; banded parts of slide seem due partly to crushing of round grains. Carbonate is secondary and not primary, because some of the rhombs are half in, half out, of the clastic grains.

"14. In light-colored part are the remains of green areas passing into tufts of actinolite (?), which, with aggregate quartz, forms the ground-mass.

"I only suggest here an outline of what appears to me to be the explanation of these slides:

"1st. The round grains in these slides owe their round form to attrition (although the resemblance to the form of oölitic grains should be noted.)

"2d. The green *glauconite* (?) is the earliest stage in these slides.

"3rd. Silicification, which is complete in the groundmass, in attacking these grains was accompanied by the breaking up of the *glauconite* into iron oxides.

"4th. The completed stage, as far as these slides go, is complete silicification of everything, the iron oxide either remaining in the clumps or more or less scattered about.

"5th. The original rock, a little back of slide 125, was a *glauconitic greensand*."

ANALYSES OF THE ORIGINAL MATERIAL.

That the material was essentially a hydrous silicate of iron, the analyses had already shown. Those rocks which contained a large amount of the original green mineral showed steadfastly a small amount of alumina, a very small amount of the alkalies, and a large amount of iron oxide, and this oxide appeared to be normally the protoxide. The analyses of numbers 14 (page 103), and 217 (page 87), especially show these characteristics. To determine more exactly the chemical composition of the mineral, rock 125 was selected, which was almost entirely made up of silica and the green mineral, with a good deal of siderite and some magnetite, but free from other impurities. From the powdered rock the magnetite was drawn out with a magnet, and the remainder of the rock, consisting only of silica, siderite, and the green material, submitted for analysis to Mr. A. D. Meeds, who made the following report:

REPORT OF ANALYSIS OF SPECIMEN 125 (CHEMICAL SERIES NO. 247).

Insoluble in hydrochloric acid.....	75.09 per cent.
Soluble in hydrochloric acid.....	24.91 " "
Total.....	100.00 " "

The insoluble portion was made up of :

Silica.....	SiO ₂	74.53 per cent.
Sesquioxide of iron.....	Fe ₂ O ₃	0.34 " "
Alumina.....	Al ₂ O ₃	0.23 " "
Total		75.09 " "

The result of the combined analyses of the soluble and the insoluble portions was as follows:

Silica.....	SiO ₂	74.53 per cent.
Alumina.....	Al ₂ O ₃	1.57 " "
Sesquioxide of iron.....	Fe ₂ O ₃	2.30 " "
Protoxide of iron.....	FeO	14.84 " "
Lime.....	CaO	.63 " "
Magnesia.....	MgO	.92 " "
Water.....	H ₂ O	.62 " "
Carbon dioxide.....	CO ₂	5.10 " "
Soda	Na ₂ O	0.11 " "
Potash	K ₂ O	0.10 " "
Total.....		100.72

The soluble portion alone, which represented the bases of the siderite and of the green mineral, had these proportions, expressed in percentages of the entire rock:

Alumina.....	Al ₂ O ₃	13.35 per cent.
Sesquioxide of iron.....	Fe ₂ O ₃	1.96 " "
Protoxide of iron.....	FeO	14.84 " "
Lime.....	CaO	0.63 " "
Magnesia.....	MgO	0.92 " "
Water.....	H ₂ O	0.62 " "
Soda.....	Na ₂ O	0.11 " "
Potash.....	K ₂ O	0.10 " "
Carbon dioxide.....	CO ₂	5.10 " "
Total.....		25.63

Since the carbonic acid must all belong to the siderite, it was then removed from the calculation, together with the necessary amount of ferrous oxide to satisfy the composition of siderite (8.35 per cent. of FeO), and the remainder, signifying the proportions of the bases in the green mineral alone, was as follows:

Alumina.....	Al ₂ O ₃	1.35 per cent.
Sesquioxide of iron.....	Fe ₂ O ₃	1.96 " "
Protoxide of iron.....	FeO	6.49 " "
Lime.....	CaO	0.63 " "
Magnesia.....	MgO	0.92 " "
Water.....	H ₂ O	0.62 " "
Soda.....	Na ₂ O	0.11 " "
Potash.....	K ₂ O	0.10 " "
Total.....		12.18

We thus obtain the exact proportion of the respective bases of the green mineral; but do not find the percentage of silica which belongs to it, since upon solution the silicate is broken up, and the silica is precipitated and cannot be separated from the original free silica of the rock. But if we assume that the mineral is a variety of glauconite, as appears from its association and optical characters, we may provisionally assign it a proportion of fifty per cent. of silica, that being about the average content of silica of this mineral, according to Dana. If, then, we figure the proportions of the other constituents as given above, to the scale of one hundred, we have the following composition of the green mineral:

Silica.....	SiO ₂	50.00 per cent.
Alumina.....	Al ₂ O ₃	5.54 " "
Sesquioxide of iron.....	Fe ₂ O ₃	8.05 " "
Protoxide of iron.....	FeO	26.56 " "
Lime.....	CaO	2.59 " "
Magnesia.....	MgO	3.78 " "
Soda.....	Na ₂ O	0.45 " "
Potash.....	K ₂ O	0.41 " "
Water.....	H ₂ O	2.54 " "
Total.....		99.92

From the same rock another portion was treated in a different way. The rock was pulverized as before, and carefully sifted and sorted into grains of nearly uniform size. As before, the magnetite was drawn out with a magnet, leaving only the silica, the siderite, and the green mineral. The different parts of this powder were then separated according to their specific gravity, by the Thoulet solution. The powder was first put into the solution having a specific gravity of 2.95. At this density about one-third of the powder was precipitated. The portion which was not thus precipitated was then put into a solution having a density of 2.80, and at this about one-third of the remaining portion came down. What still floated was then put into a solution having a specific gravity of 2.50, and in this all the remainder was quickly precipitated, leaving a clear liquid.

From this it appeared evident that the specific gravity of the green material was greater than that of the silica, probably greater than 2.80; and that the silica was therefore the lightest mineral in the section. The last portion, whose specific gravity was between 2.5 and 2.8, and which was mostly silica, was therefore thrown away; and the first two portions, whose specific gravity was over 2.8, were mingled and submitted to Mr. A. D. Meeds for analysis. This portion then consisted essentially of siderite and the green silicate, although the silica and the other minerals were so closely intermingled in the rock, owing chiefly to the fact that the silica is derived from the silicification of the green mineral, that a separation of absolute correctness could not be expected. The result of the analysis was as follows:

ANALYSIS OF GLAUCONITE AND SIDERITE FROM SPECIMEN 125 (CHEMICAL SERIES NO. 248.)

Silica	SiO ₂	47.12 per cent.
Alumina.....	Al ₂ O ₃	2.60 " "
Sesquioxide of iron.....	Fe ₂ O ₃	3.51 " "
Protoxide of iron.....	FeO	28.48 " "
Lime.....	CaO	.61 " "
Magnesia.....	MgO	1.94 " "
Potash	K ₂ O	.11 " "
Soda	Na ₂ O	trace
Water	H ₂ O	2.70 " "
Carbon dioxide.....	CO ₂	13.49 " "
Total.....		100.56

The carbon dioxide in this analysis, which belongs to the siderite, combines with 22.07 per cent. of ferrous oxide in order

to make the exact composition of this mineral, making 35.56 per cent. of ferrous carbonate (siderite, FeCO_3) and leaving 6.41 per cent. of the ferrous oxide for the glauconite.

At the withdrawal of the siderite, there remains 65 per cent. of the rock, which is composed principally of glauconite, although with a considerable impurity of free silica, which was minutely interwoven with the siderite and glauconite, and was thus brought down at a specific gravity greater than that of silica alone. By computing the elements of this residue to a scale of 100, we get the following results:

COMPOSITION OF GLAUCONITE (WITH SOME FREE SILICA.)

Silica.....	SiO_2	72.50 per cent.
Alumina.....	Al_2O_3	4.00 " "
Sesquioxide of iron.....	Fe_2O_3	5.40 " "
Protoxide of iron.....	FeO	9.86 " "
Lime.....	CaO	.94 " "
Magnesia.....	MgO	3.00 " "
Potash.....	K_2O	.17 " "
Soda.....	Na_2O	trace
Water.....	H_2O	4.15 " "
Total.....		100.02

It is probable that in this case the impurity of free silica is sufficiently important to bring down the percentage of combined silica in the glauconite to about fifty per cent. of the mineral; and then the percentages of the other components would be correspondingly greater than here appears. For this reason, it is probable that the computed composition on an assumed percentage of 50 per cent. silica, in the previous analysis, is more nearly the actual condition of the mineral.

We are thus able to draw our conclusions as to the nature of the mineral. Chemically, it is essentially a hydrous proto-silicate of iron, with a small amount of alumina, variable small amounts of calcium and magnesium, and trifling quantities of the alkalis. Chemically, it seems more closely related to glauconite than to any other mineral, and differs chiefly in the absence of the usual larger amount of potash. Another way in which it differs from the ordinary glauconite is that the iron here is normally in the protoxide state, while in nearly all the reported analyses of glauconite it is mainly in the sesquioxide condition. The nearest approach in composition of any analyzed glauconite which we can find is that from French Creek, Pa., given by Dana.*

*Descriptive Mineralogy, 6th Ed., 1892, p. 684.

The analysis of this is as follows:

Silica.....	SiO ₂	52.86 per cent.
Alumina.....	Al ₂ O ₃	7.08 " "
Sesquioxide of iron.....	Fe ₂ O ₃	7.20 " "
Protoxide of iron.....	FeO	19.48 " "
Magnesia.....	MgO	2.90 " "
Lime.....	CaO	trace
Potash.....	K ₂ O	2.23 " "
Soda.....	Na ₂ O	trace
Water.....	H ₂ O	8.43 " "

Total..... 100.18 per cent.

As an example of the chemical composition of the commoner varieties of glauconite, that from the Grodno Valley, Russia,* may be taken.

Silica..	SiO ₂	49.76 per cent.
Alumina.....	Al ₂ O ₃	8.18 " "
Sesquioxide of iron.....	Fe ₂ O ₃	16.80 " "
Protoxide of iron.....	FeO	3.77 " "
Magnesia.....	MgO	3.97 " "
Lime.....	CaO	0.41 " "
Potash.....	K ₂ O	7.57 " "
Soda.....	Na ₂ O	0.52 " "
Water.....	H ₂ O	9.82 " "

Total..... 100.00 per cent.

It is seen that the specimen from French Creek represents a departure from the ordinary composition, in the predominance of the protoxide of iron and the diminution of the amount of potassium; and the accentuation of these deviations characterizes the mineral which we have under consideration.

The specific gravity of glauconite is given by Dana† as from 2.29 to 2.35; while we have found that of our mineral as probably higher than 2.8. But the glauconite of the St. Lawrence limestone (Cambrian) of Minnesota, analyzed by Professor S. F. Peckham,‡ has, according to him, a specific gravity of 3.634; and from the chemical composition of the mineral it must be that in many cases the density rises above 3.

Optically, the mineral has been found by Professor Wolff to have all the characters of glauconite.

Its habit, so far as can be made out, is also that of glauconite, in that it occurs in disseminated grains through a sedimentary bed, and that these grains appear to have had originally rounded outlines, due to attrition.

*Ibid., loc. cit.

†Ibidem.

‡The Geology of Minnesota, Vol. II, p. 120.

We must conclude, therefore, that the mineral is probably a variety of glauconite. The characters by which it differs from the ordinary mineral may be explained in two ways. In regard to the small amount of potash, it may either be believed that this substance was absent from the original composition of the mineral, or that it has subsequently been removed by solution. But since its absence is accompanied by the presence of iron in the ferrous condition, we find it difficult to believe the latter supposition; for the same agents which would remove the alkalis would probably effect the oxidation of the iron. In regard to the excess of protoxide, again, it may be believed either that the iron of glauconite is normally a protosilicate, and that the analyses which show an excess of the sesquioxide are from more or less oxidized specimens; or, as seems more probable, there may have been an original difference. The reasons for this difference will form the grounds for future study.

THE ORIGIN OF GLAUCONITE.

The existence of the mineral glauconite has long been recognized as characteristic of the "greensand" deposits. As early as 1823 Alexander von Humboldt* mentioned the occurrence of the "green or chloritic earth" in several sandstones and limestones of different horizons in Europe. Previous to this time the glauconite had been confounded with earthy chlorite, but in 1821 the analysis by Berthier† of the greensand of the Calcaire Grossier at Paris first showed definitely its true nature, that it was essentially a silicate of iron.

Its method of formation was for a long time afterwards, however, a mystery, but in 1855 Ehrenberg‡ announced the occurrence of glauconite grains as the casts of the internal parts of species of Foraminifera, and gave the results of examinations into greensand deposits in many parts of the world. He showed that the mineral was often to be proven as having formed within these shells, and he arrived at the conclusion that in all cases this was the method of its formation, although most of the grains did not show any direct evidence of this organic origin. He not only showed this for the greensands of the more recent geological periods, but succeeded in establishing the same facts as far back as the Silurian greensand of Russia.§

*Geognostisches Versuch, p. 202.

†Annales des Mines, Ser. I. VI. 1821.

‡Über den Grünsand und Seine Erläuterung des Organischen Lebens, Berlin, 1856, p. 112. Abhandl. d. k. Akad. d. Wissenschaften zu Berlin für 1855.

§Ibid., p. 172.

In 1856, Professor J. W. Bailey* made the very important announcement that the formation of glauconite is now going on in many parts of the sea-floor, and is forming in the shells of small organisms, in the same way as had been supposed by Ehrenberg from his microscopic researches upon fossil glauconite. This discovery was brought about chiefly by material obtained by Count Pourtales† from soundings made for the United States Coast Survey.

The most recent and thorough examination of the nature and manner of formations of glauconite resulted from the work of the Challenger Expedition, sent out by the British government. The result of this investigation is found in the volume upon Deep Sea Deposits, written by Professors Murray and Renard.

Since the time of Ehrenberg, the best authorities have practically agreed that the formation of this silicate of iron is restricted in its origin to the internal chambers of organisms, in which it forms casts. Ehrenberg concluded that its origin could only be accomplished in this way. In treating of the glauconitic grains in limestone from Alabama, he writes:‡

The formation of the Greensand consists in a gradual filling up of the interior space of the minute bodies with a green-colored, opal-like mass, which forms therein as a cast. It is a peculiar species of natural injection, and is often so perfect, that not only the large and coarse shells, but also the very finest canals of the cell walls, and all their connecting tubes are thus petrified, and are separately exhibited. By no artificial method can such fine and perfect injections be obtained.

Concerning the formation of glauconite grains, Prof. J. W. Bailey wrote as follows, § in 1856:

They are now forming in the muds as they are deposited, and we have thus now going on in the present seas, a formation of Greensand by processes precisely analagous to those which produced deposits of the same material as long ago as the Silurian epoch. In this connection, it is important to observe, that Ehrenberg's observations and my own, establish the fact that *other* organic bodies than Polythalamia produce casts of Greensand, and it should also be stated that many of the grains of Greensand accompanying the well-defined casts are of wholly unrecognizable forms, having merely a rounded, cracked, lobed, or even coprolitic appearance. Certainly many of these masses, which often compose whole strata, were not formed either in the cavities of Polythalamia or Mollusks. The fact, however, being established beyond a doubt, that Greensand does form casts in the cavities of various organic bodies, there is

*American Journal of Science, Second Series, Vol. XXII, November, 1856. "On the Origin of Greensand, and its Formation in the Oceans of the Present Epoch," pp. 230-284.

†Report of U. S. Coast Survey for 1853, Appendix, p. 83.

‡Op. Cit., p. 115. "Die Bildung des Grünsandes besteht nämlich," etc. Translated by Professor J. W. Bailey, op. cit., p. 282.

§Op. Cit., p. 284.

a great probability that all the masses of this substance, however irregular, were formed in connection with organic bodies, and that the chemical changes accompanying the decay of the organic matter have been essentially connected with the deposits in the cavities, of green and red silicates of iron, and of nearly pure silica.

The opinion of Murray and Renard† is best shown by the following quotation:

From all that we have already stated in this chapter it appears certain that glauconite is principally developed in the interior of foraminiferous shells and other calcareous structures, and that all the transitions can be observed from chambers filled with a yellowish-brown mass to grains which have almost completely lost the impress of the organisms in which they were formed. From this fact, as well as from direct observations of the various constituents of the deposits, it is uncertain, and indeed little probable, that there are any minute grains of glauconite formed in a free state in the mud.

It appears, therefore, that glauconite is, so far as is known, always formed in the inner parts of organisms, and that very often the completely filled shell forms a cast which is an indication of the mode of origin. In many cases, however, the growing of the mineral inside has brought about the breaking of the shell. After the breaking of this restraining wall the shapes grow more irregular, and it seems certain that there is an enlargement of the original grain by concretionary growth from the materials which surround it. The grains which thus result may become rounded by attrition, or they may be broken so as to present angular forms; and these rounded or shattered forms vary from large grains to those of the minutest dimensions. They are thus incorporated in large numbers in the sediment, together with those rarer forms which by fortune still preserve the shape of the chambers in which they were formed.

According to Murray and Renard, the formation of glauconite is restricted to areas occupying certain positions, in regard to the shore-line and the deposition of sediment. The necessary conditions appear to be a slow deposition of very fine detrital silt, derived from terrestrial erosion, and representing the outer fringe of the land-derived sediments. Ordinarily, therefore, the glauconite-forming area is a broad zone (but much broken up by irregularities of the ocean-bottom and by currents), which lies between the Shallow-water and the Deep-water zones,—at a depth, that is to say, of from 100 to 900 fathoms. This belt follows the shore-line of the continents. It represents the transition belt between the inorganic or de-

†Reports Challenger Expedition. Vol. Deep Sea Deposits, p. 387.

trital sediments, and the mainly organic deposits. The transitional zone has a very slow rate of deposition, much more so than the landward zones where the purely detrital rocks are deposited; while it is more rapid, by the amount of land-sediment, than the beds composed exclusively of organic remains.

The union of detrital and organic matter to produce the silicate of iron, glauconite, which is characteristic of this greensand, takes place after a manner that is not well understood. It is supposed that the detrital material washes into and fills the shells, and that it is the action of the decaying organic matter inside which operates to break up the existing combinations, and to form the silicate of iron. Concerning the chemistry of the process, Murray and Renard make the following suggestions:

It is certain that very fine mud is washed into the *Globigerina* shells, and may penetrate through the foramina. If we admit that the organic matter inclosed in the shell and in the mud itself transforms the iron in the mud to sulphide, which may be oxidized into hydrate, sulphur being at the same time liberated, this sulphur would become oxidized into sulphuric acid, which would decompose the fine clay, setting free colloid silica, alumina being removed in solution; thus we have colloid silica and hydrated oxide of iron in a condition most suitable for their combination.

In greensand deposits the rounded and angular forms of the glauconite grains formed in this way make up varying percentages of the rock and are scattered throughout the finer groundmass. This ground-mass may be siliceous, or calcareous, or both; and in either case it may be made up in a considerable part of the finer glauconitic material. It is often phosphatic, bearing phosphate of lime in nodular forms. Where best developed, these glauconite grains form the larger part of the rock, making as much as 85 per cent.* This represents the most favorable conditions for the formation of this deposit. It means that the proportion of mechanical detritus and the accumulation of organic matter was almost exactly that required for the formation of the silicate. In other places, however, the glauconite is scattered sparingly, through a sandstone or a limestone. If the material is a sandstone, it was deposited nearer the center of deposition than the glauconite zone, and the diminution of glauconitic grains may be said to mark the approach to the shore. If it is a limestone, it was probably deposited in deeper waters and further from the centre of deposition than the glauconite belt, and the diminution in number of the glauconite grains marks the increasing distance from the shore.

*Ann. Rep. New Jersey Geol. Survey, 1892, p. 205.

The freshest parts of the iron-bearing rock of the Mesabi have a structure which appears to be almost exactly like that of the typical greensand, although hardened and consolidated. The grains of glauconite have a similar shape and arrangement, and in the sections cut from specimen 53-1, they are somewhat intermingled with grains of carbonate. Between these grains there is the same fine ground-mass, which in this case seems to be of finely divided silica. In this specimen, moreover, the consolidation is not so great as in the more altered common varieties; the fracture is irregular, and the surface of fracture granular, instead of being smooth and conchoidal, as happens when the processes of change have gone on to a greater extent. The shapes of the green grains and their distribution through the ground-mass show a decided resemblance to the figures of sections of greensand made by Ehrenberg* and Murray and Renard.†

This same structure is characteristic of the more altered rocks, where it has been called the spotted-granular structure. Professor Wolff, in the letter quoted on a former page, first called attention to the fact that the granules as a whole bore evidence of detrital origin, and suggested that they represented the altered original glauconitic grains. Subsequent study has brought the writer to believe that most of these areas owe their existence primarily to the original grains of glauconite, although their form and composition has been altered by various mechanical and chemical changes. The stages of transition from the simply glauconitic granules to those where the granules are formed only of the decomposition products, chiefly silica and the iron oxides, make this seem evident. In the later stages of the rock, however, not only have the changes profoundly altered the original granule, but these forces have often produced new granules, simulating closely the older ones which were derived from the truly detrital grains. These new granules are composed chiefly of the material derived from the alteration of the old ones, but they occupy new positions and have new forms. The nature of these secondary forces and their effects have already been described, as granular-brecciation, concretionary action, impregnation, and other forces, in various combinations.

*Op. cit. plate VI. Lower Silurian greensandstone of Russia.

†In Challenger Reports. Reproduced by New Jersey Geol. Surv. for 1892, p. 242, plate V. fig. I.

We have probably, therefore, in the Animikie (the Upper Huronian of the United States Geological Survey) one of the most extensive deposits of greensand which have ever been known to accumulate. The succession of strata here is suggestive, as complying with the present conditions of the deposition of glauconite. The basal quartzite represents the deposition of a considerable period, when the area lay near the shore-line, and in the region of direct arenaceous sediments. The conglomeratic phase near the base seems to have represented a still nearer approach to the shore, and during the subsequent deposition there may have been a slight subsidence. At the close of the deposition of the quartzite, and the beginning of the deposition of the iron-bearing member, we may believe that there was a marked subsidence, which brought the area out of the reach of direct arenaceous sediments, and into a depth and distance from shore which was favorable for the formation of glauconite, with intermixed siliceous and calcareous matter.

At this time there was sparing detrital mud from the land area, and we must believe, in accordance with the known conditions for the formation of glauconite, that there was abundant organic life. The essential result of the combination of this decaying organic matter and the detrital mud was the union of the iron and the silica to form glauconite. This glauconite, as already stated, seems to have been originally a hydrous protosilicate of iron, without much potash or any other essential constituent. For these peculiarities we must look for the reason in the peculiarities of the sediment which prevailed, since it is to the variations in the composition of this that the varying composition of glauconite appears to be due.

The most marked characteristic is perhaps the absence of potash. But it must be remarked that this constituent, while commonly an important feature, does not seem to be essential. Glauconite from the Calcaire Grossier of the Paris Basin, analyzed by Berthier,* gave the following results:

Silica.....	.....SiO ₂	40.00 per cent.
Alumina.....	.....Al ₂ O ₃	1.00 " "
Protoxide of Iron.....	.....Fe ₂ O ₃	} 24.70 " "
Sesquioxide of Iron.....	.....FeO	
Lime.....	.....CaO	3.30 " "
Magnesia.....	.....MgO	16.60 " "
Potash.....	.....K ₂ O	1.70 " "
Water.....	.....H ₂ O	12.60 " "
Total.....		100.00 per cent.

*Annales des Mines, 6, 1821, p. 459.

It is seen in this analysis that the potash is one of the least important constituents of the rock. In another analysis * by the same chemist, no potash nor soda were reported. These analyses were the first to determine the actual nature of glauconite, and were accepted as the standard composition of the mineral. Many analyses† show only between three and four per cent. of potash; while a specimen analyzed by Murray and Renard,‡ from off the coast of Australia, afforded less than one per cent.

While the iron and the silica for the formation of the glauconite are derived directly from detrital mud, it is stated by Murray and Renard that the potash must be derived from the sea-water in which it exists in solution. The sea-water derives it from the fragments of the land-derived rocks which accumulate upon the bottom. The discussion is concluded as follows:

If we recall the observations with reference to the geographical distribution and mineralogical and lithological association, it seems possible to suggest, with a considerable degree of certainty, the relative abundance of potash in the deposits where glauconite is forming. It was pointed out that glauconite was always associated with terrigenous minerals, and in particular with orthoclase, more or less kaolinized, and white mica, and with the debris of granite, gneiss, mica-schists, and other ancient rocks. We cannot fail to be struck with these relations, for it is just those minerals and rocks that must give birth by their decomposition to potassium, derived from the orthoclase and the white mica of the gneisses and the granites.§ The minute particles of these rocks and minerals, which make up a large part of the muddy matters settling on the bottom beyond the mud-line around continental shores, would readily yield under the action of sea-water the chemical elements that are deposited in the form of glauconite in the chambers of foraminifera and other calcareous organisms.

In this case, it becomes necessary to consider what was the nature of the rocks whence the sediments of the glauconite-building zone were derived. Older than this formation, except the basal and underlying quartzite, which is conformable and therefore can have contributed little sediment to the glauconite zone, there are only the altered and schistose rocks and granites of the pre-Animikie formations. The granite of the Giant's

*Annales des Mines, 6, 1821, p. 459.

†Ann. Rep. New Jersey Geol. Survey, 1892, p. 228.

‡Reports Challenger Expedition, Vol. Deep Sea Deposits, 1892, p. 387.

§It has been shown, in fact, by Guignet and Telles, that the water of the Bay of Rio Janeiro contains a large amount of potassium salts, evidently due to the presence of ancient rocks in this bay. (See Comptes Rendus, tom., lxxxiii, p. 919, 1876).

range has already been briefly described, as well as those Kewatin schists which lie to the south of the granite belt, on the Mesabi range. It is not as yet possible to say exactly what was the land surface at the time of the deposition of the iron-bearing member, but it seems to have been of the general nature of the complex of pre-Animikie rocks which occupies the whole north-eastern part of the state, to the north of the Giant's range, and it may well have included this actual region. These schists, gneisses and granites appear to have been in practically the same condition as now, at the time of the deposition of the Animikie sediments, as previously shown.

It seems at first as if we have here rocks which, according to Murray and Renard, in the quotation just made, should furnish an abundance of potassium, and that the glauconite should normally contain a larger percentage of the same mineral, if this region were actually the land surface adjacent to the shoreline. There has as yet been made no thorough study of the rocks of this region, but so far as is known, these rocks, instead of containing an unusually large amount of potash, have an unusually small quantity. Several analyses of granites from this region have invariably shown that the rock was a soda-granite, with a small, often insignificant amount of potash.* One of these analyses is of granite from the Kawishiwi river, and contained 5.01 per cent. of soda, with 1.68 per cent. of potash. Another, of the granite at Saganaga lake, contained 4.33 per cent. of soda, and 0.71 of potash. Although these are perhaps extreme cases, they do not seem to be uncommon, and the other analyses support the statement that, so far as has yet been ascertained, the ancient granite of this area, which is of pre-Animikie age, is pre-eminently a soda-granite, and contains an unusually small amount of potassium.

Concerning the schists, which is the other source from which the sediments of the iron-bearing member must have been chiefly derived, we have, as in the case of the granites, not enough knowledge to make positive assertions; but so far as is known, there is in these rocks the same small amount of potash. These schists are mainly basic, and a large part of them are probably of either direct volcanic origin, or have been derived from volcanic rocks through some assorting and rearranging under atmospheric conditions.

*Twenty-first Ann. Rep. Minn. Geol. and Nat. Hist. Survey, pp. 41 and 43.

An analysis of Keewatin green schist from Tower gave the following results: *

Silica	SiO ₂	50.47 per cent.
Alumina	Al ₂ O ₃	18.45 " "
Sesquioxide of iron	Fe ₂ O ₃	2.13 " "
Protoxide of iron	FeO	7.74 " "
Lime	CaO	6.61 " "
Magnesia	MgO	6.90 " "
Potash	K ₂ O	0.30 " "
Soda	Na ₂ O	2.58 " "
Phosphoric acid	P ₂ O ₅	traces.
Water	H ₂ O	2.34 per cent.
Total		97.52

Another analysis of a rock of this sort, † from the falls of the Kawishiwi, south of Fall lake, shows the following composition. Analysis by C. F. Sidener:

Silica	SiO ₂	43.96 per cent.
Alumina	Al ₂ O ₃	16.03 " "
Sesquioxide of iron	Fe ₂ O ₃	10.50 " "
Protoxide of iron	FeO	8.73 " "
Lime	CaO	9.54 " "
Magnesia	MgO	6.56 " "
Potash	K ₂ O	0.27 " "
Soda	Na ₂ O	1.62 " "
Water	H ₂ O	1.84 " "
Total		99.06

Professor G. H. Williams, in his work on "The Greenstone Schist Areas of the Menominee and Marquette Regions of Michigan," ‡ has made a more thorough study of these older schists in another part of the Lake Superior country. As far as can be seen, the schists of Minnesota are identical in very many respects with the rocks here described, and so the results of this work may be compared with interest, although with caution. These rocks were found in a large part to be altered eruptives, mainly basic in character; and most of the analyses given show a large amount of soda, and a small quantity of potash. § Occasionally the reverse is the case, but in the region as a whole, the small amount of potash is marked.

Thus, so far as we can go, the region from which the iron-bearing rocks derived their sediments was one in which the rocks contained potassium in very sparing quantity, both in the schists and in the gneissic and granitic rocks. It will probably lead to interesting results to investigate this subject

* Seventeenth Ann. Rep. Minnesota Geol. Survey, p. 126.

† Bulletin No. 6, Minn. Geol. Survey, p. 38.

‡ Bulletin of the U. S. Geol. Survey, No. 62.

§ Ibid., pp. 76, 89, 91, 104, 113, 119, 121, 121, etc.

still further, and to discover whether this rule actually holds for the whole or a large part of this area.

While thus neither the granites nor the schists could contribute much potassium to the formation of the glauconite, the detritus from the basic schists contained a large quantity of iron, and formed an abundant supply for the growth of the deposits.

The change at the top of the iron-bearing member to the calcareous horizon indicates a further subsidence of the area, so that the distance from the shore-line became so great that under the conditions very little mechanical detritus was brought, and the deposit was mostly made up of calcareous matter, probably of organic derivation. There is mingled with the lime, however, much fine green material which appears to be glauconitic, and so it is probable that through this zone there was still some of this substance formed. Above the limestone horizon comes the great body of siliceous slates. This indicates a rather sudden change from the previously existing condition, and an abundant supply of fine sediment. This was probably the result of an elevation of the area, so as to bring it within the mud zone; but the change of sediments may have been occasioned simply by a change of currents, caused by disturbances in some other locality.

In the Cretaceous and Eocene greensand of New Jersey* there is a succession of strata which is somewhat similar to that which is found in the Animikie rocks, resulting from a gradual subsidence of the area of deposition. Immediately below the glauconitic beds is the Raritan formation, composed chiefly of sands and clays; and a shallow water sediment, as is shown by various evidences.† The conditions of its deposition may be somewhat broadly held to correspond with that of the lower quartzite of the Animikie. Above the Raritan formation the beds are glauconitic for a considerable thickness, though the amount of glauconite varies in different horizons, apparently according to changing conditions of deposition. These beds are called the Clay Marl Formation, the Lower Marl Bed, the Red Sand Formation, the Middle Marl Bed, the Upper Marl Bed, and the Shark River Marl. Throughout these divisions the glauconitic beds contain horizons which are largely argillaceous or calcareous. The whole series is overlaid by shallow-water Miocene sediments.

In extent these greensands are comparable with the iron-bearing beds of the Animikie. The estimated thickness of the

* Annual Rep. New Jersey Geol. Survey, 1892, pp. 169-239.

† Ibid., 1892, p. 183.

various beds of the glauconitic zone amounts to over five hundred feet, and the lateral extent was great. In the preliminary map of portions of Monmouth and Middlesex counties, accompanying the report of the New Jersey Geological Survey referred to, and apparently including only a small portion of the greensand districts, these glauconitic beds occupy an area of over three hundred square miles.

For the characteristics by which the Mesabi iron-bearing rock differs from more recent greensand deposits, we have to consider the extreme length of time during which it has been exposed to degradational and reconstructive processes. Not only the structure of the rock, but also the chemical composition, has thus been permanently changed. In the ground-mass which originally surrounded the glauconitic grains, we may believe that there was originally some calcareous matter, as well as siliceous; but this limy matter would be one of the first things to be removed by the dissolving waters. The poverty of the rocks in phosphates is probably to be explained in the same way, as compared with the phosphates in the New Jersey and other greensand deposits. The phosphate of lime, which we may believe, from analogy with more modern deposits, was present, in the shape of nodular masses scattered through the ground-mass, was easily soluble and quickly removed. To the great lapse of time must also be chiefly ascribed the possibility of decomposing so thoroughly the glauconite, and concentrating the resulting minerals. Deposits of iron ore of workable value arising in this manner are not known by the writer to have been described in any of the more recent formations, although Penrose* suggests that "the glauconites of the Upper Cretaceous of Texas may have in part afforded a supply of iron for the Tertiary deposits, while the Tertiary glauconites have probably had but little to do with the formation of Tertiary ores, though they may become a source of iron for future ore deposits."

Possibility of Finding Traces of Organic Forms.

With a view to finding whether the forms in which the glauconitic grains sometimes occur have any resemblance to organic bodies, a thin section from the freshest specimen collected, 53-1, was submitted to Dr. Robert T. Jackson of Harvard University, and to his kindness the following expression of opinion is due:

"I have examined your slide carefully and should say that there is no evidence of organic structure in any part of it. The

*The Iron Deposits of Arkansas, Ann. Rep. Ark. Geol. Surv., 1892, vol. I. p. 120.

round or rounded grains of crystallized calcite (as I suppose), are apparently concretionary aggregations, and cannot safely be considered as organic or replacements of organic matter. The 'glauconite' particle in the centre of the indicated field shows superficial striated structure, but is unlike anything I know in Foraminifera. It has no appearance of organic matter, and its structure is doubtless of mechanical origin.

"In rocks as old as those under consideration, you would need very good material to prove organic material. This slide certainly does not show it. I showed the slide to Mr. B. H. Van Vleck, who is a very competent judge in the microscopic structure of plants and animals, and he positively affirmed that it showed no organic structure. I also showed it to Professor Alpheus Hyatt, who coincided in the opinion."

It is not impossible, however, that further study of more favorable sections may succeed in finding the traces of the organisms which may once have existed in these rocks. A close comparative study of the glauconite grains would very likely be rewarded as well as research in any other field; and the light that such discoveries would throw upon the conditions of this as yet almost unknown period would be of the greatest value.

NOMENCLATURE.

Although the various rocks of the iron-bearing member have been minutely described, yet no name has been found which seems to be applicable even to the more ordinary phases of the rock. Originally the rock was probably a greensand, with more or less siliceous and calcareous matter; but in the greater part of the rocks there are very few traces of the original structure and composition. The term "greensand" is hardly applicable to a firmly consolidated rock. Ehrenberg calls the consolidated greensand of Russia "greensandstone" (grünsandstein); but neither is this term applicable to this altered rock. A greensandstone bears the same relation to greensand as does sandstone to sand; but the rock of the iron-bearing member of the Animikie may be supposed to bear a relation to greensandstone somewhat similar of that of a profoundly altered quartzite to a sandstone. It seems necessary, then, to have a means of designating this altered greensand.

Upon the Mesabi range, the term "taconyte" has come into very general use as a designation of the iron-bearing rock in general. This term was first proposed by Mr. H. V. Winchell for the rock enclosing and constituting the ore-bodies.*

*Twentieth Ann. Rep. Minn. Geol. Survey, p. 124.

Whatever may be the opinion as to the fitness of derivation of this word, it has obtained such currency, especially upon the Mesabi Iron range, as seems to warrant its retention. It is therefore proposed that the term be applied to rocks of this character, which appear to be altered greensandstones. The nature of the typical taconyte may then be briefly described as follows:

The rock consists of a ground-mass of silica, which is usually cryptocrystalline, although it may be finely phenocrystalline, or chalcedonic. In any case, the silica is evidently secondary, and a precipitation from solution. Through this ground-mass are scattered rounded or angular bodies, which have been called granules. These perhaps average a thirtieth of an inch in diameter. They represent partly original grains of glauconite, partly the result of the processes of metasomatism, and are composed of glauconite, siderite, hematite, magnetite, limonite, or cryptocrystalline silica, these minerals occurring either singly or associated in all proportions in the different granules of different phases of the rock. There are the accessory minerals actinolite, calcite (magnesite), chlorite? kaolin? pyrite, epidote and apatite. There is no original crystal form in the rock, and the essential minerals generally do not show it. As a result of secondary crystallization, it is often seen in the magnetite and siderite, and always in the actinolite. Among the most important minerals, where several occur together, the relation is such as to show that one is derived from the other, and that the glauconite has been the original mineral whence all the others have been formed, as the more or less reconstructed products of its decomposition. Among its physical peculiarities, the rock may be said to be generally hard, with a fracture that varies from conchoidal to irregular; no cleavage, but a tendency to a prismatic vertical and a parallel horizontal jointing. In color it may be various shades of gray, red, or green, according to the varying composition.

Taking this rock as a type, the more altered types which are derived from the same source may be designated by prefixing the word "taconyte," indicative of their origin, to the word which expresses their physical peculiarities. Thus there may be "taconyte slates," "taconyte clays," "taconyte chert," "taconyte jasper," and so on. No word, however, can be used as the last term in these appellations which implies an origin contrary to the one explained. It is not possible, for example, to have a "taconyte sandstone" or a "taconyte quartzite," although the rock may in its physical peculiarities somewhat simulate a sandstone or a quartzite.

CHAPTER XII.

SUMMARY STATEMENT*.

In the few succeeding pages a concise statement of the more important principles with which this bulletin deals will be attempted.

LIMITS OF THE MESABI RANGE.

The Mesabi range in Minnesota may be for convenience separated into three geographical divisions, characterized by sufficient geological differences: The Western Mesabi, which extends from the Mississippi river to the Embarras lakes, on the eastern edge of range 16 W.; the Eastern Mesabi, reaching from the Embarras lakes to the region of Gunflint lake; and the International Boundary division, which stretches from Gunflint lake east to Pigeon point. In the Western Mesabi region lie all the mines at present worked, and it is to this section alone that the observations made in this chapter are intended to be strictly applicable. The chief ore-bearing district lies between the Mesabi Chief mine on the west and the Hale on the east, a distance of about forty miles.

GENERAL STRUCTURE.

The lowest rocks of the region are greenish schists, which belong in the Keewatin formation. These schists are cut by a great belt of intrusive granite, which runs the entire length of the iron-bearing district and usually forms the summit of the divide between the Mississippi and the Red River basins. Unconformably upon these older rocks lie the gently dipping Animikie strata.

There are three chief members of the Animikie in the iron-bearing regions, as definitely known at present. Lowest is a

*This chapter is substantially as published in the *American Geologist* for May, 1894, in a paper entitled "The Iron Ores of the Mesabi Range."

quartzite; upon this lie the iron-bearing rocks; and finally there is a great thickness of black slates. The base of the slates is calcareous, and becomes in places an impure limestone, often dolomitized or sideritized.

The iron-bearing rocks occupy a definite and constant horizon between the quartzite and the slates. They are marked by peculiar and characteristic features, and have always been recognized as invariably associated with the ore deposits. They seem to have a nearly uniform thickness, which may be estimated as between 500 and 1,000 feet, with an average of perhaps 800 feet.

MINOR STRUCTURE OF THE ANIMIKIE.

The ore-bearing region of the Western Mesabi affords a peculiarly valuable field for investigation, for the rocks have suffered only very slight disturbance since the time of their deposition. The general structure is a monocline, which dips slightly east of south, at a gentle angle, which averages perhaps ten to fifteen degrees. On the eastern end of the Western Mesabi there has been some slight additional disturbance. There is evidence leading to the belief that a wedge shaped area eight or ten miles in length, lying mainly in T. 58-17, has been faulted up above the surrounding rocks; the amount of vertical displacement being perhaps 500 feet. This may be called the Virginia area, from the town of that name which is in the vicinity. To the east of this upthrust area there is as far as the Embarras lakes at least (a distance of five or six miles), a gentle folding of the strata, which appears to have been contemporaneous with the faulting. These disturbances may be provisionally believed to have occurred in later Keweenawan or post-Keweenawan time, and to have been contemporaneous with the monoclinal tilting.

CHARACTER OF THE IRON-BEARING ROCKS.

The rocks of the iron-bearing member exhibit great diversity. The most common sort is massive and siliceous, and is thickly spotted with small round darker areas, consisting mainly of iron oxide. From this there are many deviations; and often the different varieties cannot be said to resemble one another in any way, either in the field or under the microscope, or on chemical investigation. But specimens are constantly found which show one variety changing into another. Thus it soon became evident to the writer that all the rocks of the

iron-bearing member, however different, were closely allied in origin, and were probably derived from a single primitive type. This same principle has already been shown by Irving and Van Hise for the Penokee-Gogebic rocks.*

NATURE OF THE ORIGINAL ROCK.

A careful macroscopic and microscopic study of a large number of carefully selected specimens was made, with very satisfactory results. Nearly every detail of the changes from one phase into another could be made out and the causes assigned. The changes were seen to be those of metasomatism, and the inciting agents seemed mainly atmospheric. The original rock of the series was quite unmistakable. Typically it may be briefly described as follows:

In a ground mass of cryptocrystalline, chalcedonic, or finely phenocrystalline silica, are thickly strewn rounded or sub-angular bodies, made up chiefly of a green mineral, very slightly pleochroic, and without cleavage; under crossed nicols it appears in some places amorphous, in others extinguishing as an aggregate.

Analyses showed this mineral to be essentially a hydrous silicate of iron, and selected sections kindly examined by Dr. J. E. Wolff, of Harvard University, were stated by him to "resemble in all physical characters *glauconite*." In one especially fresh specimen there were also rounded grains of calcite (probably magnesian), apparently originally detrital, and in some limited areas these increased in number till they formed nearly the whole bulk of the rock. These glauconitic carbonate layers are nearly identical in appearance with the glauconitic St. Lawrence (Cambrian) limestone of Minnesota, of which sections were cut and compared. Dr. Wolff suggested tentatively that the rock was an altered greensand. This appears to the writer to be the correct view. There is, however, a peculiar feature shown by chemical analyses—a constantly very small amount of potash.

THE PROCESSES OF CHANGE.

It is quite certain that from this rock are derived nearly all the other phases in the iron-bearing member. In the alterations there are various processes, differing by reason of the varying forces which have been brought to bear upon the rocks.

*Tenth Ann. Rep., U. S. Geol. Survey.

The most common, which may be called the *normal process*, appears to take place under scant access of atmospheric agents. The decomposition of the green mineral is the noteworthy event. It breaks up, forming chiefly silica and the iron oxides or carbonate, so that in by far the commoner phases of the rocks the rounded bodies or granules are composed entirely of these decomposition products.

The various stages in the rearrangement of the silica and the iron oxides or carbonate constitute the succeeding phases. The chief cause of their separation lies in the different conditions under which these two chief constituents are taken into solution. From very careful study of the separation and concentration of the silica and the iron, there may be deduced two rules. First, in regions of comparatively free oxidation, chalybeate waters deposit iron and remove silica. Thus bands of iron are formed along cracks and fissures, whether macroscopic or microscopic, replacing the silica; and isolated spots weakened by weathering become by replacement blotches of iron oxide. Conversely, in regions of extremely scant oxidation, waters deposit silica and remove iron in solution. Thus the portions which are most porous become richer in iron and lose their silica; this iron is derived mainly from the adjacent unoxidized parts of the rock, and into these unoxidized parts the silica from the oxidized portions is constantly carried. The final result is an almost complete separation of iron and silica.

CHEMISTRY OF THE PROCESS.

The chemistry of this process seems to be approximately as follows:

Most atmospheric waters contain, among other things, carbonic acid, oxygen, and certain amounts of the alkaline salts. Carbonic acid gives water the power of taking iron into solution; while the alkaline salts are slower but ready solvents of silica, especially in the finely divided cryptocrystalline or chalcedonic state in which it is usually found in these rocks. These waters find their way into the rock, and to some degree into the firmest portions. As they begin to penetrate inward from the crevice along which they came, the oxygen unites with the unoxidized elements of the rock, decomposing some of the minerals, and extending the *weathered zone*. By the decomposing action of this oxygen, carbonic acid may be set free; and the same product may result from the action of

acids, either brought in by the water or developed during decomposition. The water thus passes further into the rock free from oxygen, but highly charged with carbonic acid. Aided by the pressure under which it is placed, it readily dissolves the iron. The affinity of the alkaline solvents for the silica is so much weaker than that of the carbonic acid for the iron that the water becomes saturated with iron, without any appreciable quantity of silica being taken up. The solution finally finds its way again out into a zone of greater oxidation, such as a crack. Upon the access of oxygen and the release of pressure, most of the iron is precipitated. As the solvent power of the water is now renewed, the alkaline salts become able to take silica into solution. Thus iron replaces silica. Next the water again finds its way into an unoxidized region, and under these conditions again takes iron into solution, which compels the precipitation of some of the silica; so that here silica replaces iron. Finally, this process brings about an almost complete separation of the two minerals.

THE CONCENTRATION INTO BANDS.

Most often weak and firm parts alternate closely in the rock, usually being arranged in narrow horizontal zones. If the weak zone is one of comparatively scanty oxidation, the iron may be deposited as carbonate; if of freer oxidation, as the hydrous sesqui-oxide. So in the final concentration we may have a very well defined banding of cherty silica with siderite; or, more usually on the Western Mesabi, bands of silica (usually ferruginous), alternate with bands of iron oxide (usually siliceous). The crystallization of the latter gives the typical "jasper and ore," which is occasionally found on the Western Mesabi, but is not so common as in others of Lake Superior iron regions.

RESULTS OF ACCUMULATED STRAINS.

The change from the oxides of iron to the carbonate, and from the carbonate back to the oxides, has been found by study with the microscope to be very common, and the same iron may repeatedly undergo the metamorphosis, with changing conditions. When the most of the rock is thus altered, there is an appreciable change of bulk, the oxidation of the carbonate being attended by contraction, and the carbonatation of the oxides by expansion of the rock. The loss of the more soluble products of decomposition has also a marked

contractile effect, very early in the rock's decay. These contractile and expansile tensions, occurring sometimes in different parts of the field, often successively in the same part, have given rise to many of the physical peculiarities of the rock. Among the effects of the contractile tensions there is a very common smooth, vertical, prismatic jointing, and the development of closely set horizontal joints, which somewhat simulate cleavage. It is these horizontal joint-cracks which become the seat of deposition of the iron from the percolating waters; and thus the parallelism of the banding is explained. With the advance of decomposition, the horizontal cracks become more numerous, and the bands of iron which are formed along them often grow till they unite. It is to this cause that the beautifully bedded character of the ore-deposits must be chiefly ascribed.

The expansile strains lead to breccias, and to local faulting and folding, especially in the ore bodies. They also give rise to shearing movements, which have in many places altered the rocks for a limited distance and induced a schistose or slaty structure. This shearing process forms one of the chief deviations from the normal process of change.

VARIATIONS FROM THE NORMAL PROCESS.

Another important modification of the usual manner of change follows the exposure of a considerable area to freely oxidizing forces. This condition is nearly always found at the surface, and often deep into the rock, following zones of weakness, induced chiefly by regional disturbances. In these parts of the rock the various stages of decomposition and concentration are hurried forward with such comparative swiftness that the phases of rock thereby produced are different than those produced by the normal process. In these rocks the iron is concentrated into large bodies and impure disintegrated silica and clay is left behind. Thus, among the ferrated rocks, the ore-bodies are formed. Among the leached rocks the most common are the "paint rocks," which have, subsequent to their leaching, usually become iron-stained, so that they form a stiff clay, red, yellow or brown in color; also a cream white residual clay, which has been mistaken for kaolin. On analysis the last proves to be mainly free silica, with a small amount of silicate of alumina and impurities; and, in one place at least on the Western Mesabi, it is a nearly pure silica powder.

Least important among the causes of change has been the impregnation of the rocks by minerals apparently derived from without the iron-bearing member and brought by percolating waters. Calcite is the chief of these minerals; and the calcitized portions of the iron-bearing rock are distributed near the contact with the calcareous stratum of the black slates.

THE FORMATION OF THE ORE-DEPOSITS.

It has already been stated that the bands of iron owe their existence to previously formed zones of weakness. From the narrow band there may be found every gradation upward in size, till the body of iron becomes large enough to merit the name of an ore-deposit. These ore-deposits are often very large, being occasionally nearly a mile in their longest extent. The ore is usually hematite, loose and granular, and when of best quality is of a blue or brown color. Typically there is a portion, near the surface, which has become hydrated into yellow limonite or göthite. Often these ore-bodies rest upon the basal quartzite; often again they rest upon the hard and little-altered iron-bearing rock itself. The conditions under which they form seem identical with those necessary for the growth of the narrow bands of iron in the banded "jasper and ore." In both cases the iron has concentrated in an area of especial weakness. In the case of the band the cause of the small area of weakness has already been explained. In considering the cause of the formation of the ore-bodies, it is only necessary to find the cause of the development of so great regions of weakness.

The richest ore producing region thus far developed is that which lies in T. 58-17, and surrounds the Virginia area, following the supposed fault lines. Immediately east of these lies another rich group, near Biwabik, in the somewhat disturbed strata adjacent to the upthrust area. At the Mountain Iron mine there is strong microscopic evidence of a disturbance, probably a fault, while at the other important mines there has not been sufficient exploration to enable one to determine their peculiarities. So the conclusion may be reached that the most important of the ore-bodies owe their existence to regional disturbances which have produced large areas of weakness. Faults, especially, are accompanied by the development of such areas, and in folded regions the summits of anticlines, and to a less degree the troughs of synclines, are weakened.

In the opening up of a great area of weakness, moreover, such as attends a fault-plane, a channel for the surface waters to find their way down is often afforded, and the shallow underground drainage for a considerable distance is deflected into the fault-fissure. The increased supply of water, emerging saturated with iron from percolating through the decomposing iron-bearing rocks, is an important factor in the formation of the ore. The chemistry of the process is practically the same as for the small oxidized areas which produce bands. Waters emerge heavily laden with iron into this zone of oxidation; here they precipitate their iron and are enabled to take into solution and carry away some small quantity of silica. The effect of the underlying impermeable quartzite is important, since it deflects the surface waters into the weak zone, instead of absorbing them. Owing to the crystalline nature of its quartz, it is hardly or not at all replaced by iron, and thus it forms an unaltered stratum, even in the weakened zone, upon which the ore-body may accumulate.

In addition to this, smaller ore-bodies may be formed near the surface, at the bottom of the highly weathered zone, and resting upon the little-altered rock below. Inequalities in the decomposition produce small basins in the hard rock below, in which waters collect and finally deposit their iron.

It may be noted that the impervious dikes, which have been shown by Irving and Van Hise to have been important in the concentration of the iron in the ranges of the South Shore, especially in the Penokee-Gogebic, have played no part upon the Mesabi. Upon the whole length of the Western Mesabi there has not yet been discovered a single dike or other igneous rock in the Animikie.

It must be remembered that in no single case has an ore-body been mined out, or even explored sufficiently to give a complete knowledge of its features, so that much valuable information must come to light in the future.

DATE OF THE CONCENTRATION.

There is no positive evidence as to the exact time of the disturbances which ultimately brought about the formation of the great ore-bodies. It may be considered, however, pending evidence to the contrary, that they were contemporaneous with the monoclinical tilting, and that they occurred in later Keweenawan or immediately post-Keweenawan time.

The Eastern Mesabi.

The Eastern Mesabi differs in regard to its iron from the Western Mesabi in that it contains a much larger proportion of magnetite, which is associated with somewhat more crystalline silica. As these peculiarities are associated with the presence of the igneous rocks of the Keweenawan, and since they fade out as the distance from the Keweenawan area increases, it appears probable that, as has been suggested by H. V. Winchell,* the advent of these rocks was in some way connected with the magnetic condition of the iron. If this be the case, we must conclude that most of the banded magnetite of the Eastern Mesabi has been concentrated prior to Keweenawan time. But the lack of large ore-bodies in this region shows that up to this time the concentration had not occurred on a very large scale. It is probable that the same force which produced magnetization put a serious check upon the separation and concentration of the constituents of the rocks, causing the degree of concentration in that region at the present time to be behind that of the Western Mesabi.

The Cretaceous Conglomerates.

There are upon the Mesabi small patches of Cretaceous rocks, lying upon the Animikie strata. In the area examined, they are chiefly conglomeratic, and the fragments are mainly derived from the iron-bearing rocks. A study of these fragments shows two things; first, that at the time of the formation of the conglomerate there existed hard iron ore in the iron-bearing member; and, second, that much of the rock has been decomposed and has had its iron concentrated subsequently to being taken into the Cretaceous beds.

We may conclude that the process of concentration has been going forward since early Keweenawan or pre-Keweenawan time, and there is abundant evidence that it is going on at the present day.

SUMMARY.

The most important conclusions to which the study of the iron-bearing rocks of the Mesabi have led may be briefly recapitulated as follows:

I. At the beginning, the rock was probably of sedimentary nature, consisting mainly of glauconitic grains, with probably

*Twentieth Ann. Rep., Minn. Geol. Survey, p. 136.

some associated calcareous and siliceous matter. All these materials are believed to have been derived by the reconstructive action of marine organisms, upon fine detrital silt from subaerial erosion, in moderately deep seas, somewhat remote from shore.

II. The elevation of these beds brought them under the reach of atmospheric influences. Percolating surface waters dissolved out whatever calcareous ingredients there may have been, and brought about the decomposition of the glauconite. This silicate, from its unstable form, quickly broke up, forming, chiefly, silica and iron oxide.

III. The various stages of decomposition of this original rock, as well as those of certain reconstructive processes of the same, have brought about the variations which characterize the present phases of the iron-bearing rock.

IV. The normal last stage of the decomposition of the original rock and the concentration of the resulting products, is the separation of the silica and the iron into separate bands or bodies.

V. The iron is concentrated in the regions of greatest oxidation; the silica in the regions of least oxidation. Large bodies of iron, therefore, have collected in extensive areas of great oxidation. The formation of these weak areas is accomplished in various ways, but on the Mesabi chiefly by disturbances of the strata arising from regional strains. The development of these strains is supposed to have taken place in later Keweenawan time.

PLATE V.

THIN SECTIONS FROM THE IRON-BEARING ROCKS.

Figure 1.

Section 53-1-C. From a well at the camp of the Chicago mine, S. E. $\frac{1}{4}$ S. E. $\frac{1}{4}$ Sec. 4, T. 58-16. Specimen taken from the iron-bearing rocks at the contact with the upper slates. In the ordinary light; magnified about 60 diameters. This rock represents the least altered phase found upon the Mesabi range. The ground-mass is of very finely divided quartz. Through this are seen thickly strewn the rounded and irregular forms of the granules. The dark granules are of glauconite, green, or brown from separation of iron oxide. In the large granule at the right the process of silicification has gone on, so that now most of its bulk is occupied by the cryptocrystalline silica which has replaced the glauconite. In the central and lower part of the figure, grains of carbonate (calcite or dolomite), probably originally detrital, may be recognized by their cleavage. Some of the clear spots in the glauconite areas, especially at the extreme left of the figure, are grains of quartz, which are probably directly detrital.

Figure 2.

Section 130. From S. E. $\frac{1}{4}$ S. E. $\frac{1}{4}$ Sec. 18, T. 58-19. In the ordinary light; magnified 25 diameters. The ground-mass is of very finely divided phenocrystalline quartz; the granules, whose outlines are seen in the figure, as in the section, with all degrees of distinctness, are made up chiefly of uncrystallized iron carbonate and cryptocrystalline silica, with small residual areas of glauconitic material. The original glauconitic material has been in this section almost entirely decomposed, resulting in the separation of silica, and iron in the form of carbonate, with a very slight amount of iron oxide. The peculiar ringed and spotted structure (see Plate VI), which characterizes the silicification process, is still preserved, and may be dimly seen in the large granule near the lower right-hand corner. This figure is especially intended to illustrate the process of *granular-brecciation*. Here the breaking up of the granules under the stress of tensions, developed within the rocks as a result of the chemical changes, may be noted.

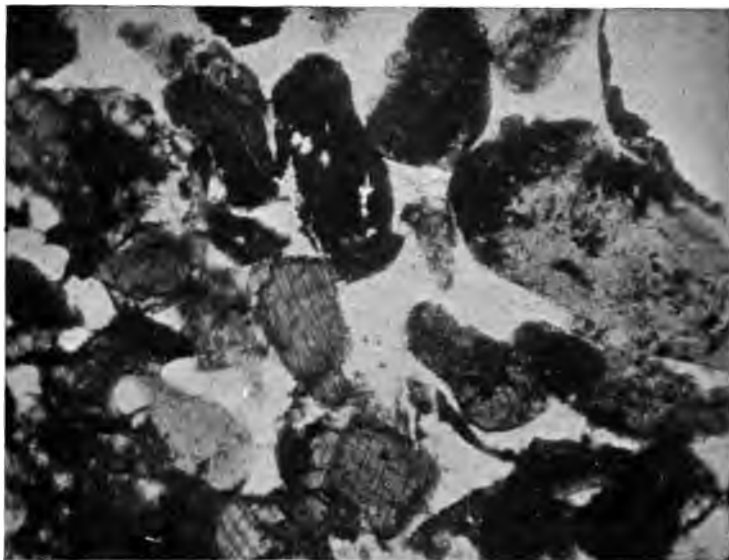


FIGURE 1.

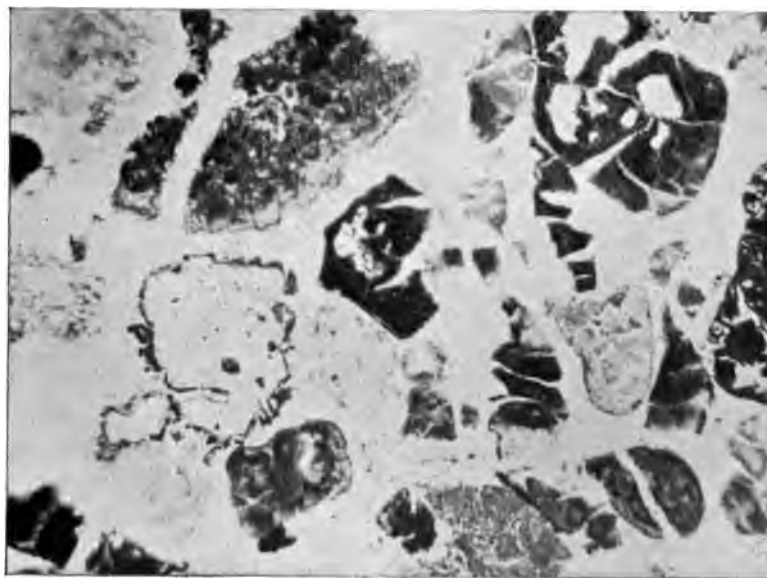


FIGURE 2.

THIN SECTIONS FROM THE IRON-BEARING ROCKS.

PLATE VI.

THIN SECTIONS FROM THE IRON-BEARING ROCKS.

Figure 1.

Section 125. From Section 17, T. 58-19. In the ordinary light; magnified 20 diameters. Ground-mass of silica, finely divided phenocrystalline to finely divided cryptocrystalline. The solid dark granules are of green glauconite. The spotted and faintly outlined granules are composed mainly of cryptocrystalline silica, always markedly finer in grain than that of the ground-mass, together with siderite, both uncrystallized and crystallized, and a very small amount of iron oxides, chiefly magnetite. All stages of the formation of these siliceous and fast disappearing granules from the unaltered glauconitic bodies may be seen. In this section also, some of the effects of granular brecciation may be seen.

Figure 2.

Same section as figure 1; magnified 50 diameters. In this section the large dark granule is the same as that seen in the upper left-hand corner of figure 1. This is intended to show the phenomena of the process of decomposition of the glauconite. The solid dark granules are entirely of unaltered glauconite. The granule just above the solid dark granule in the lower left hand corner shows the beginning of decomposition; the large irregular granules in the center show the process well advanced; while in the area in the extreme lower left-hand corner it is almost completed. Note the small rings of silica which characterize the process, which are surrounded by glauconite and enclose a core of the same material.

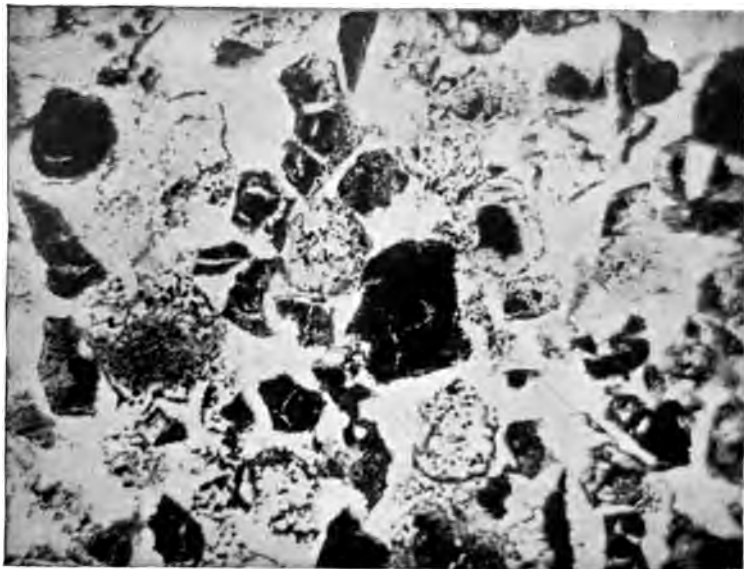


FIGURE 1.

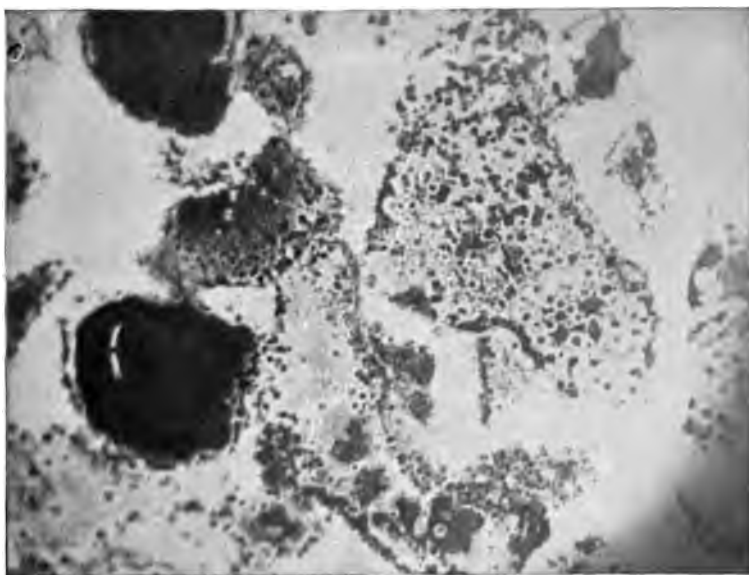


FIGURE 2.

THIN SECTIONS FROM THE IRON-BEARING ROCKS.

PLATE VII.

THIN SECTIONS FROM THE IRON-BEARING ROCKS.

Figure 1.

Section 78. From N. W. $\frac{1}{2}$ S. W. $\frac{1}{2}$ Sec. 2, T. 58-18. In the ordinary light; magnified 50 diameters. The lighter colored portions of the figure are of very finely divided cryptocrystalline silica. In polarized light the rounded forms of the granules are very distinct, on account of the somewhat finer grain of the silica of which they are made up. Otherwise the granules are characterized in general only by some disseminated iron oxide, which is usually hardly more than a staining, and often is not present at all. The result of the disintegration of the original glauconitic material (small residual fragments of which are still seen in some parts of this section), has been the separation of the silica and the removal of most of the iron. The spotted-granular structure is thus nearly effaced, as is evident from the figure, and the rock approaches the condition of a chert. The scattered iron is beginning to crystallize as siderite, in granules and ground-mass alike. The rock is thus an intermediate stage between the normal spotted-granular rocks and the sideritic cherts. Note the zonal structure of the siderite crystals, showing their growth by successive additions.

Figure 2.

Section 143. From N. E. $\frac{1}{2}$ N. E. $\frac{1}{2}$ Sec. 19, T. 58-19. In the ordinary light; magnified 20 diameters. The lighter colored parts of the figure, both in the ground-mass and in the granules, are of very finely divided silica. The dark portions are entirely of iron oxide, mostly magnetite. The iron oxide shows a concentric arrangement which is probably due, in part at least, to concretionary action. The nuclei around which these rings have formed, however, are usually the granules which have been figured and described above. Where the iron has been removed from these they are hardly visible, especially in the ordinary light; such granules may be distinguished in the upper and right hand parts of the figure. No trace of the original glauconitic material remains in this section.

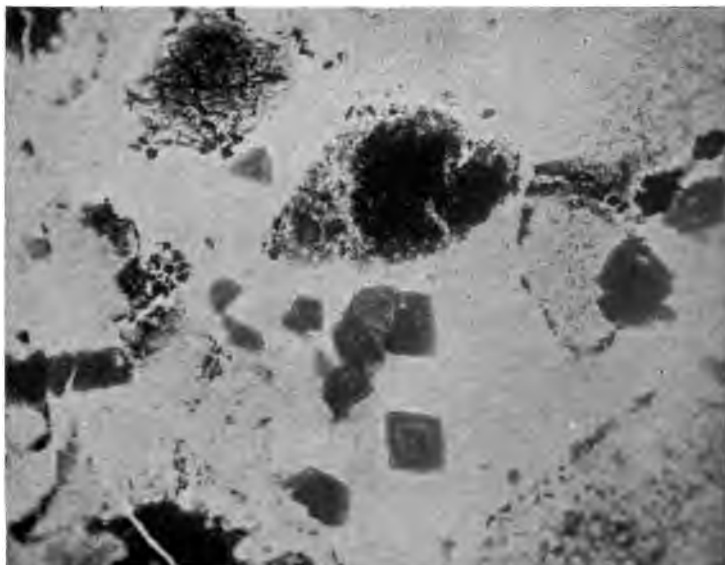


FIGURE 1.

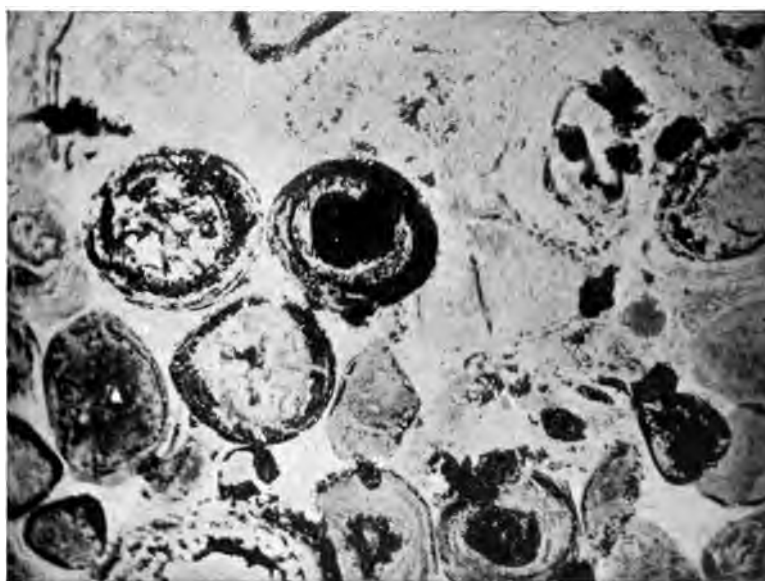


FIGURE 2.

THIN SECTIONS FROM THE IRON-BEARING ROCKS

PLATE VIII.

THIN SECTIONS FROM THE IRON-BEARING ROCKS.

Figure 1.

Section 53-1-B. From same specimen as Plate V, figure 1. In the ordinary light; magnified 30 diameters. This is at the beginning of the process of change. The ground-mass is of cryptocrystalline to finely phenocrystalline silica. The dark granules are mainly of the dark-green glauconitic material. There is a good deal of carbonate (mainly calcite or dolomite) scattered through the section. Grains of this, apparently originally detrital may be recognized by their cleavage, in the upper left-hand part of the figure.

Figure 2.

Section 10. From N. W. $\frac{1}{2}$ N. W. $\frac{1}{4}$ Sec. 2, T. 58-17. In the ordinary light; magnified 30 diameters. This is near the end of the process of change. The section is composed entirely of silica and magnetite. The silica varies from finely phenocrystalline. In general the original ground-mass cannot be distinguished from the original granular areas; in some cases, however, under crossed nicols, the granules may still be distinguished. The distribution of the magnetite has no relation to the nearly-obliterated granular areas. In this section the decomposition of the original material has been quite completed. The iron, moreover, instead of remaining to mark the position of the granules, as in an earlier stage, has been leached out and has crystallized throughout the rock. In the figure the angular crystal outlines of the magnetite masses may be distinguished.

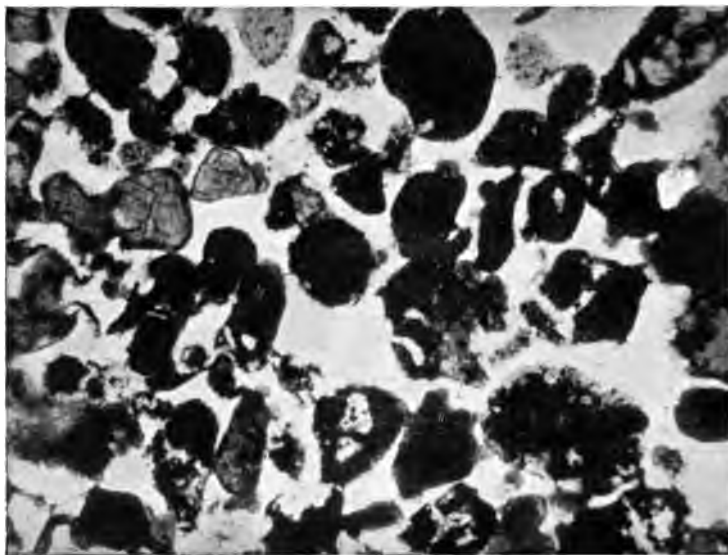


FIGURE 1.

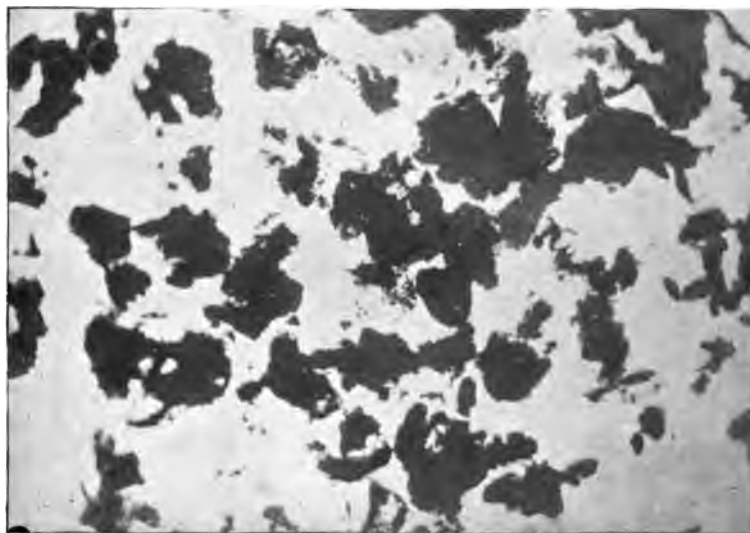


FIGURE 2.

THIN SECTIONS FROM THE IRON-BEARING ROCKS

PLATE IX.

PECULIAR STRUCTURES OF THE IRON-BEARING ROCKS.

Figure 1.

Specimen 36. From the Chicago property, in the S. E. $\frac{1}{4}$ S. E. $\frac{1}{4}$ Sec. 4, T. 58-16. Slightly reduced from actual size. This rock is in the process of decomposition, and the decay is proceeding from centers scattered throughout the mass, thus giving the peculiar pitted appearance. The pits start around a cluster of iron oxide or carbonate, which has segregated during the stages of dissolution and concentration. From these centers the decay spreads till the whole rock becomes disintegrated.

Figure 2.

Specimen 68. From N. W. $\frac{1}{4}$ N. W. $\frac{1}{4}$ Sec. 2, T. 58-18. Slightly reduced from actual size. This is one of the brecciated taconyte jaspers which are common upon the Mesabi. In a dark-gray spotted-granular ground-mass are scattered fragments of finer-grained rock, jasperoid, with a conchoidal fracture. These fragments are usually completely oxidized to a bright red color, although in some cases only the periphery has been oxidized, and the rest of the fragment remains in color gray, like the ground-mass. A large fragment of this sort, with an oxidized border, may be seen in the right-hand part of the figure, just below the specimen number. Under the microscope, the structure of the unaltered fragments is found to be essentially the same as that of the ground-mass. The origin of this breccia is in chemical causes. The rock has been shattered by the discharge of accumulated strains arising from metasomatic changes.

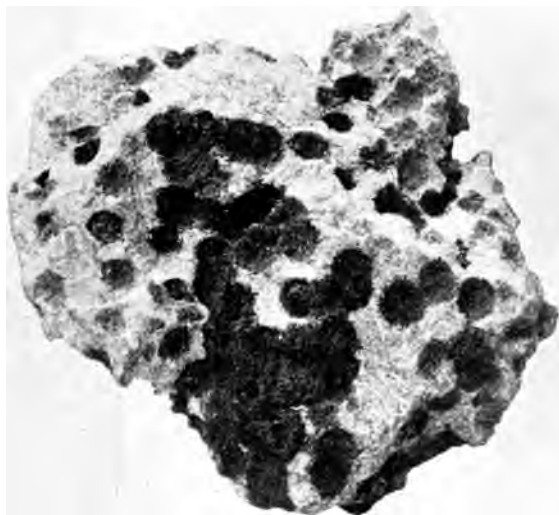


FIGURE 1.

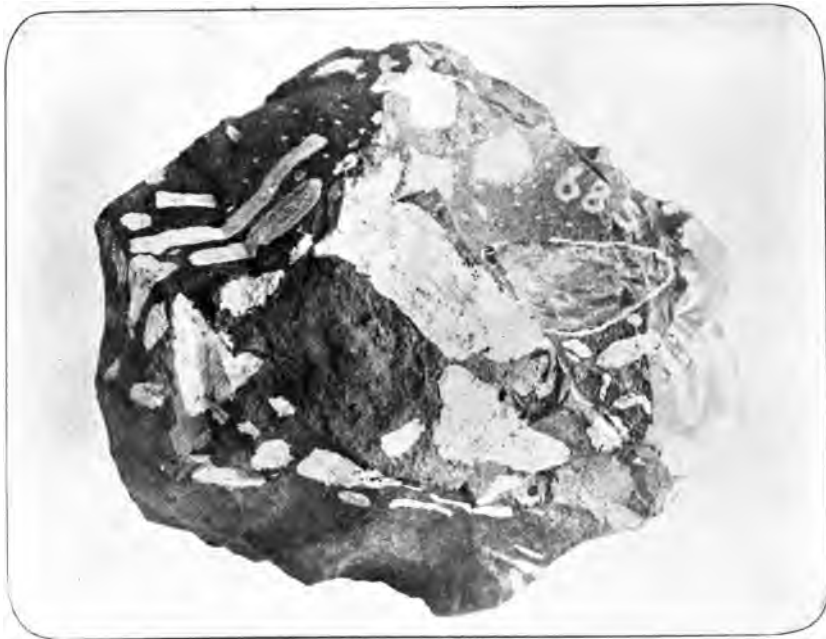
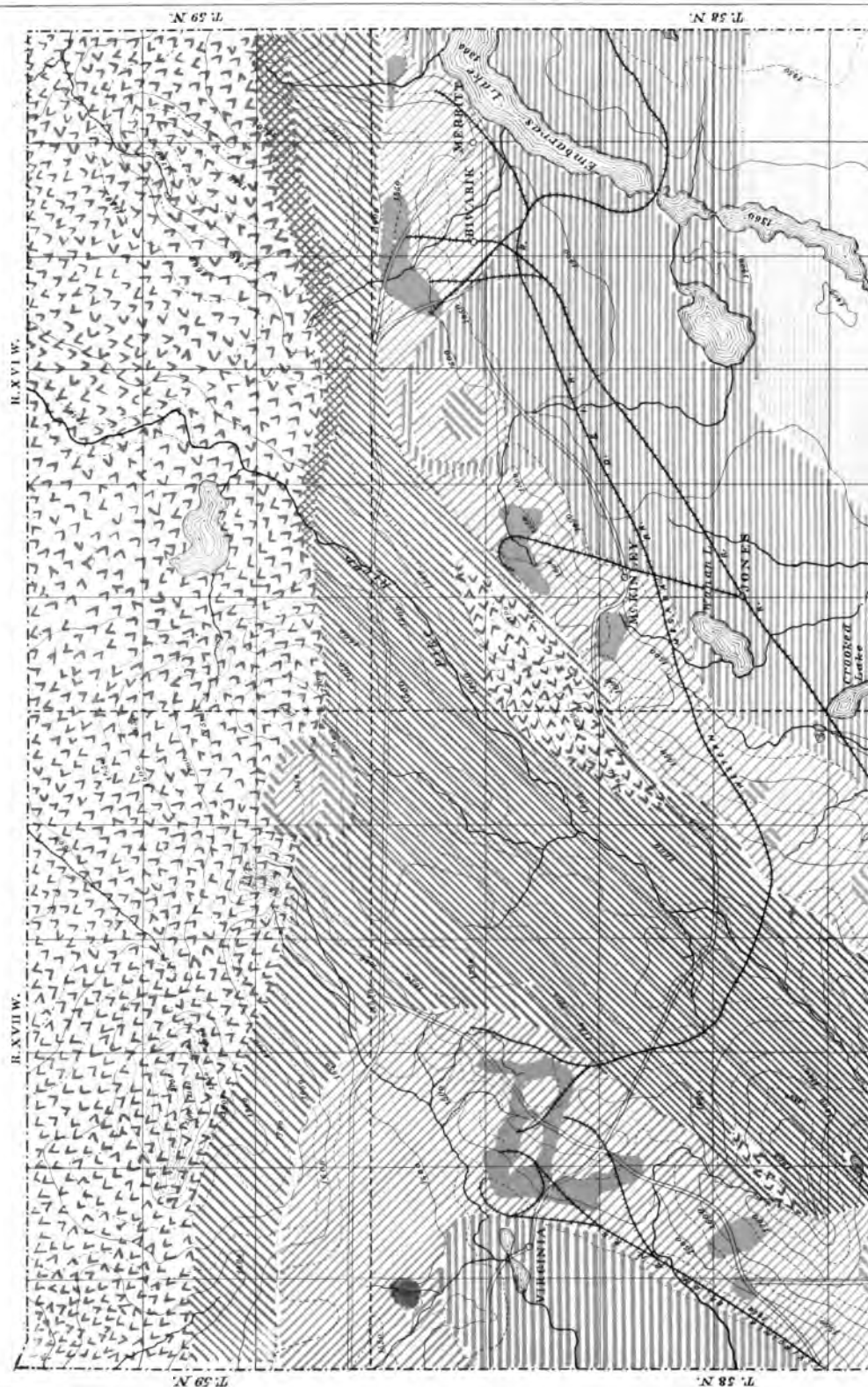
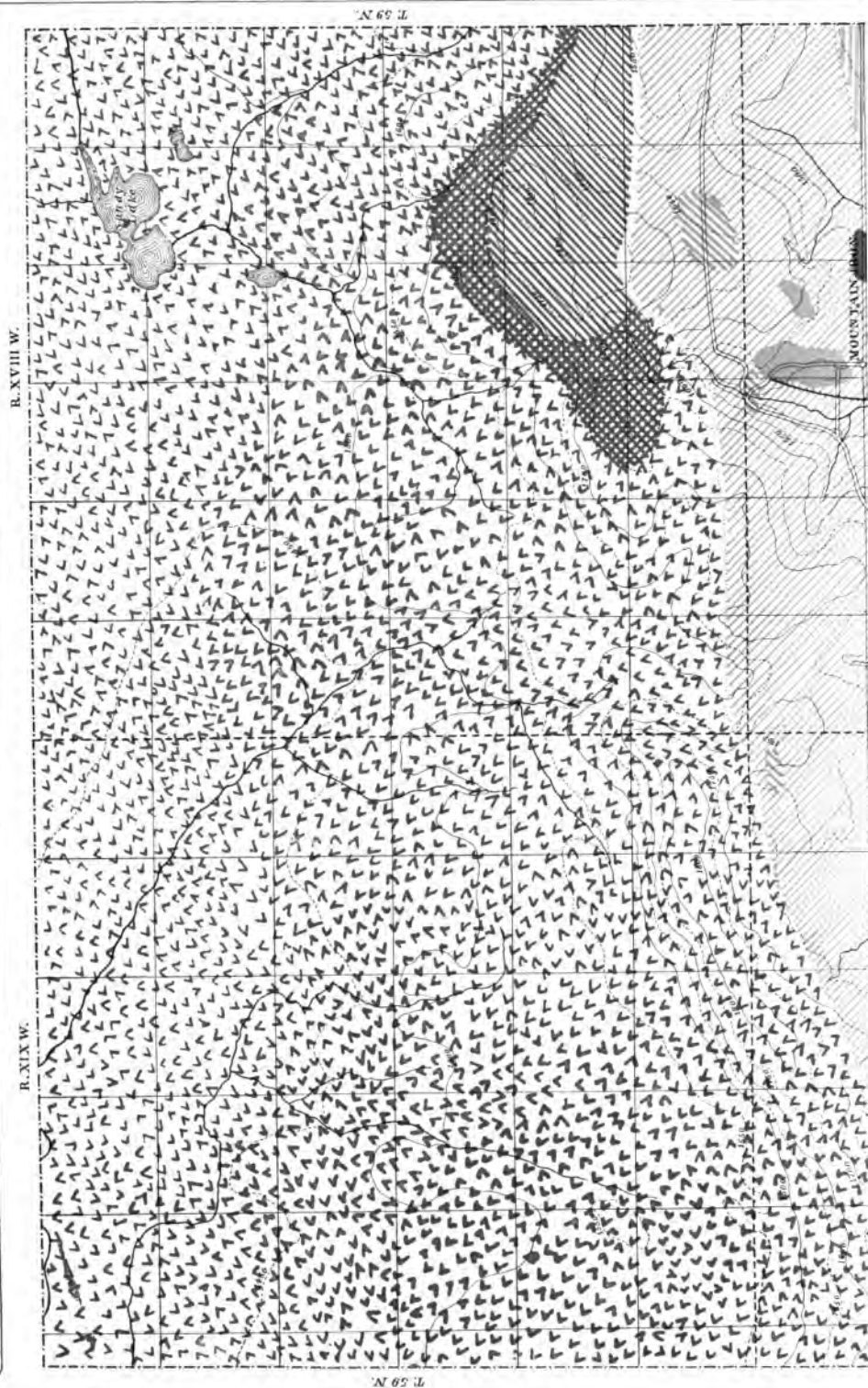
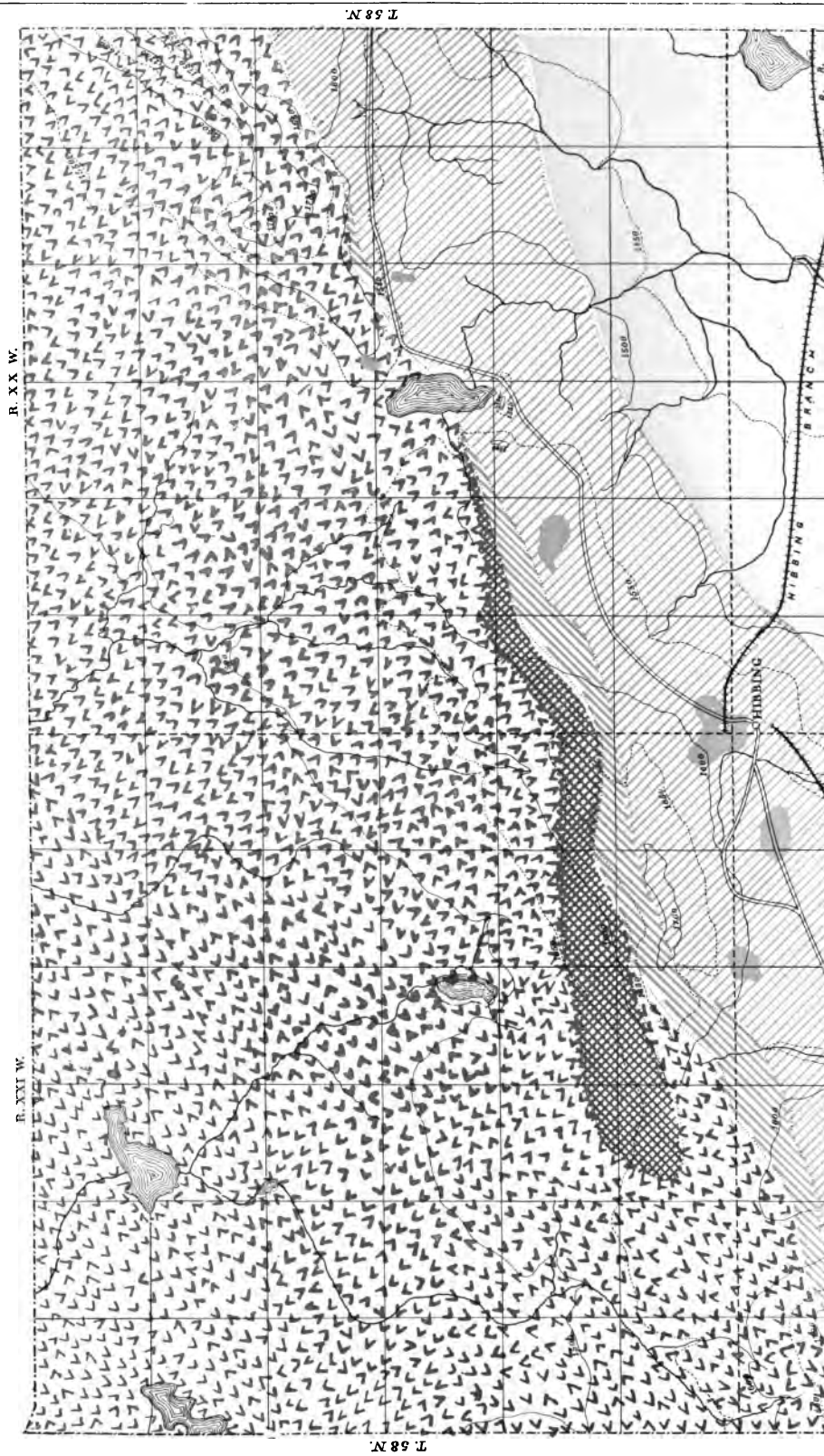
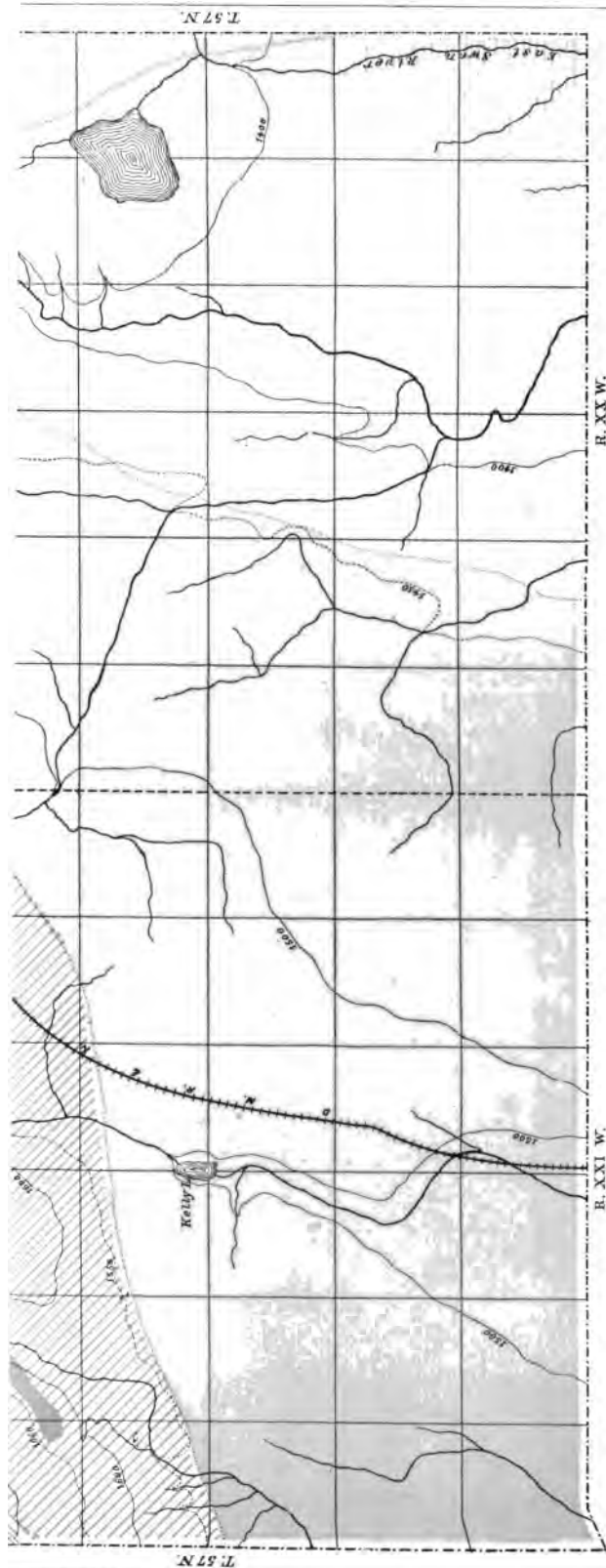


FIGURE 2.
PECULIAR STRUCTURES OF THE IRON-BEARING ROCKS.









GEOLOGICAL AND NATURAL HISTORY SURVEY OF MINNESOTA. **HIBBING PLATE OF THE MESABI IRON RANGE,** **BY J. E. SPURR.**

Contour Lines are drawn approximately }
for each fifty feet above the sea.

EXPLANATION OF COLORS.

GLACIAL DRIFT.	CRETACEOUS.	TACONIC (ANIMIKIE)	ONTARIAN.
<p>Concealing other formations.</p> <p>Till</p>	<p>Conglomerates and shales.</p>	<p>Iron Bearing Member, Barren Rock, Ore-bodies.</p>	<p>Post-Keweenaw, Granite (intrusive).</p>
<p>Modified.</p>	<p>Black Slates.</p>	<p>Quartzite.</p>	<p>Keweenaw & Couchiching* Green, sericitic schists, and Micaceous schists.</p>

* The Couchiching is a lithological modification of rock whose age is to be considered the same as the Keweenaw.

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